The NOνA Experiment:
Phase 2 of the Fermilab NuMI Program

NuSAG
Gaithersburg
1 June 2005

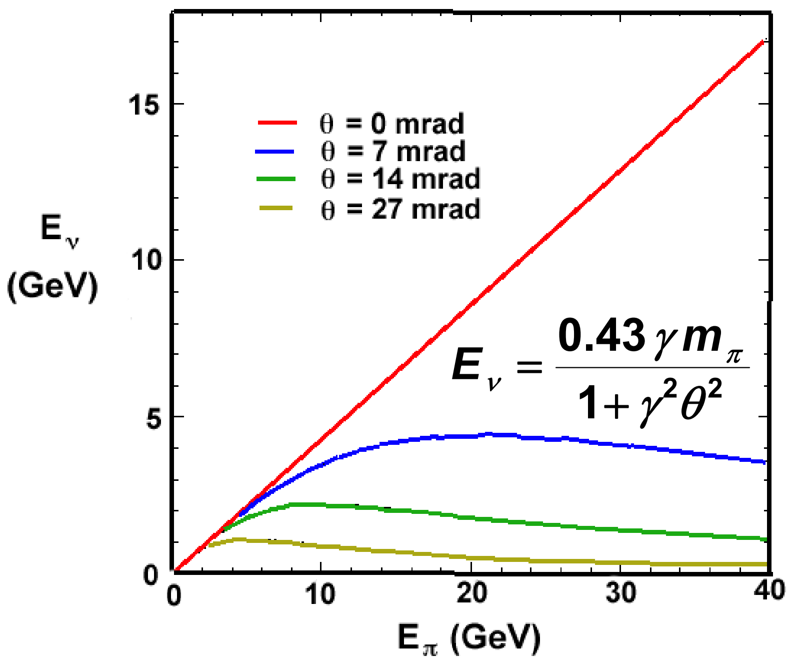
Gary Feldman

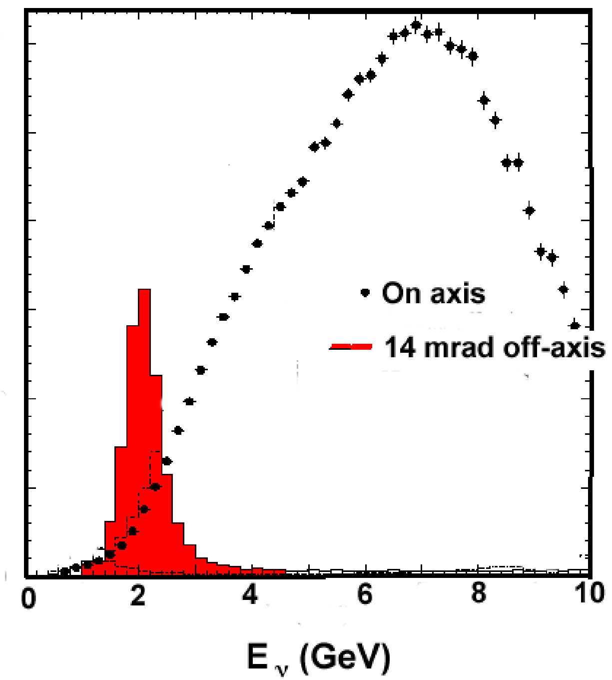
The NOνA Experiment
(NuMI Off-Axis ν_e Appearance Experiment)

- NOνA is an approved Fermilab experiment optimized for measuring ν_e appearance with the goal of improving MINOS's $\nu_\mu \rightarrow \nu_e$ measurement by approximately an order of magnitude.
- The NOνA far detector will be
  - a 30 kT "totally active" liquid scintillator detector
  - located 15 mrad (12 km) off the NuMI beamline axis near Ash River, NM, 810 km from Fermilab
- The uniqueness of NOνA is the long baseline, which is necessary for determining the mass ordering of the neutrino states.

Off-Axis Rationale

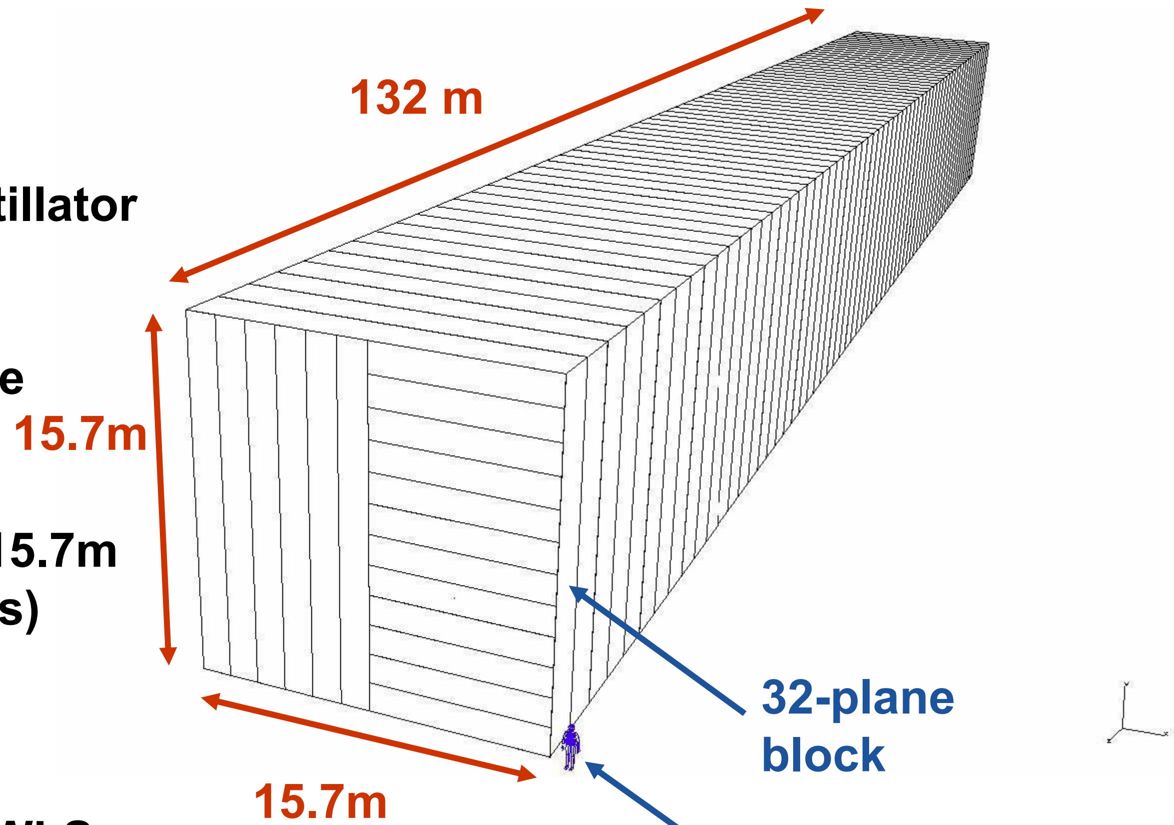
- **Both Phase 2 experiments, NOνA and T2K are sited off the neutrino beam axis. This yields a narrow band beam:**
  - **More flux and less background (ν_e's from *K* decay and higher-energy NC events)**



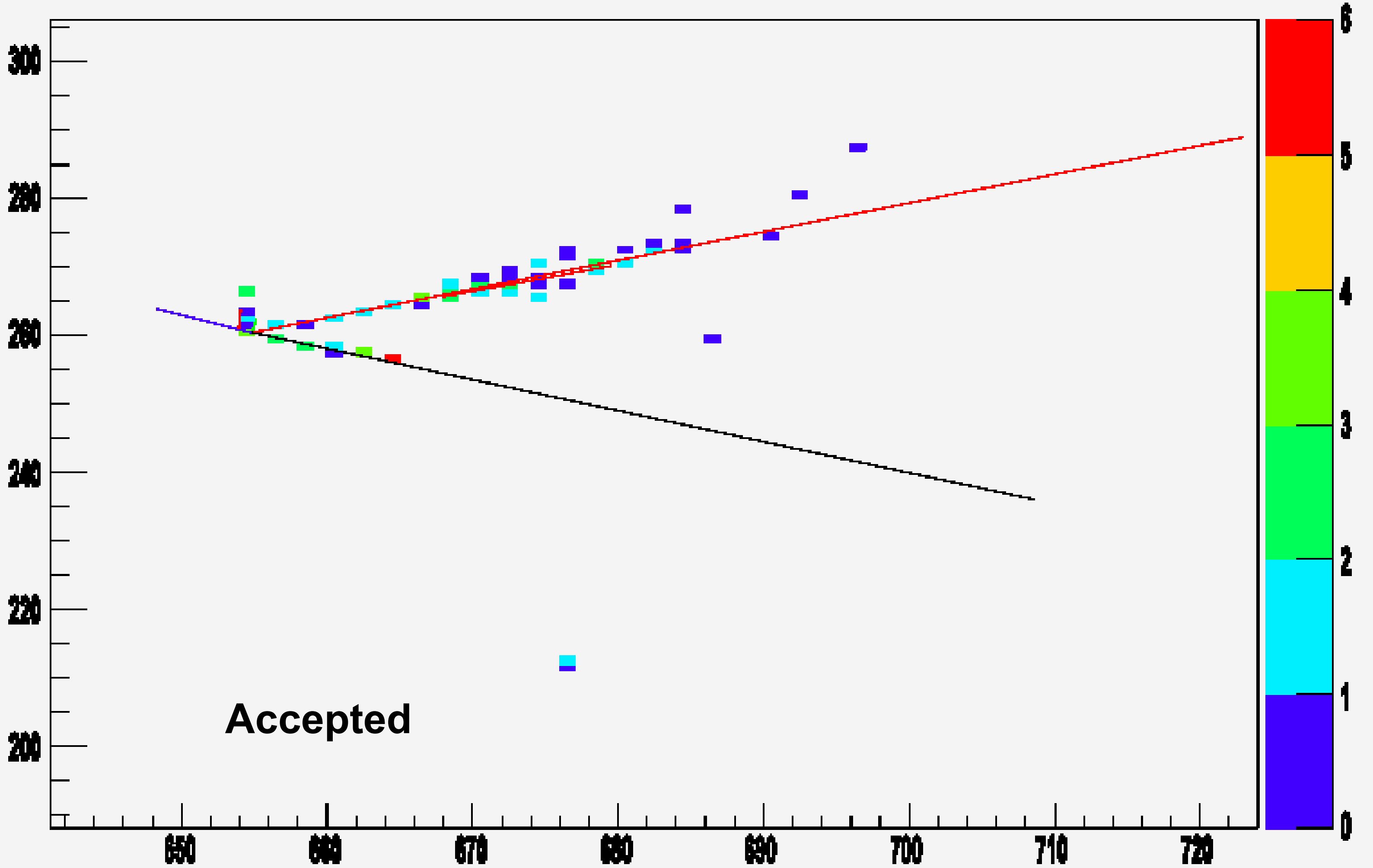


NOvA Far Detector

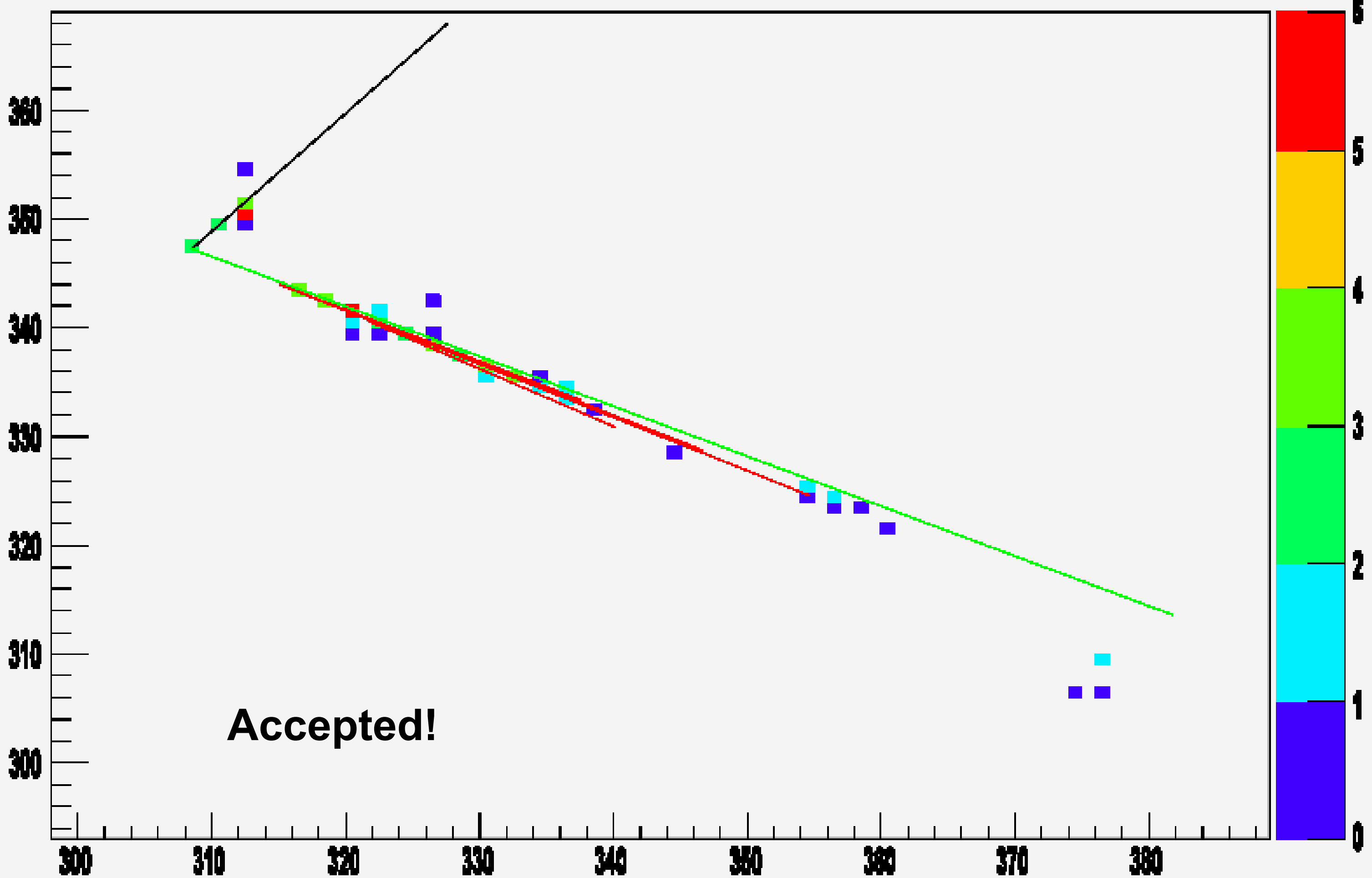
“Totally Active”
30 kT:
  24 kT liquid scintillator
  6 kT PVC
32 cells/extrusion
12 extrusions/plane
1984 planes
Cell dimensions:
  3.9 cm x 6 cm x 15.7m
  (0.15 X_0 thickness)
Extrusion walls:
  3 mm outer
  2 mm inner
U-shaped 0.8 mm WLS fiber into APD



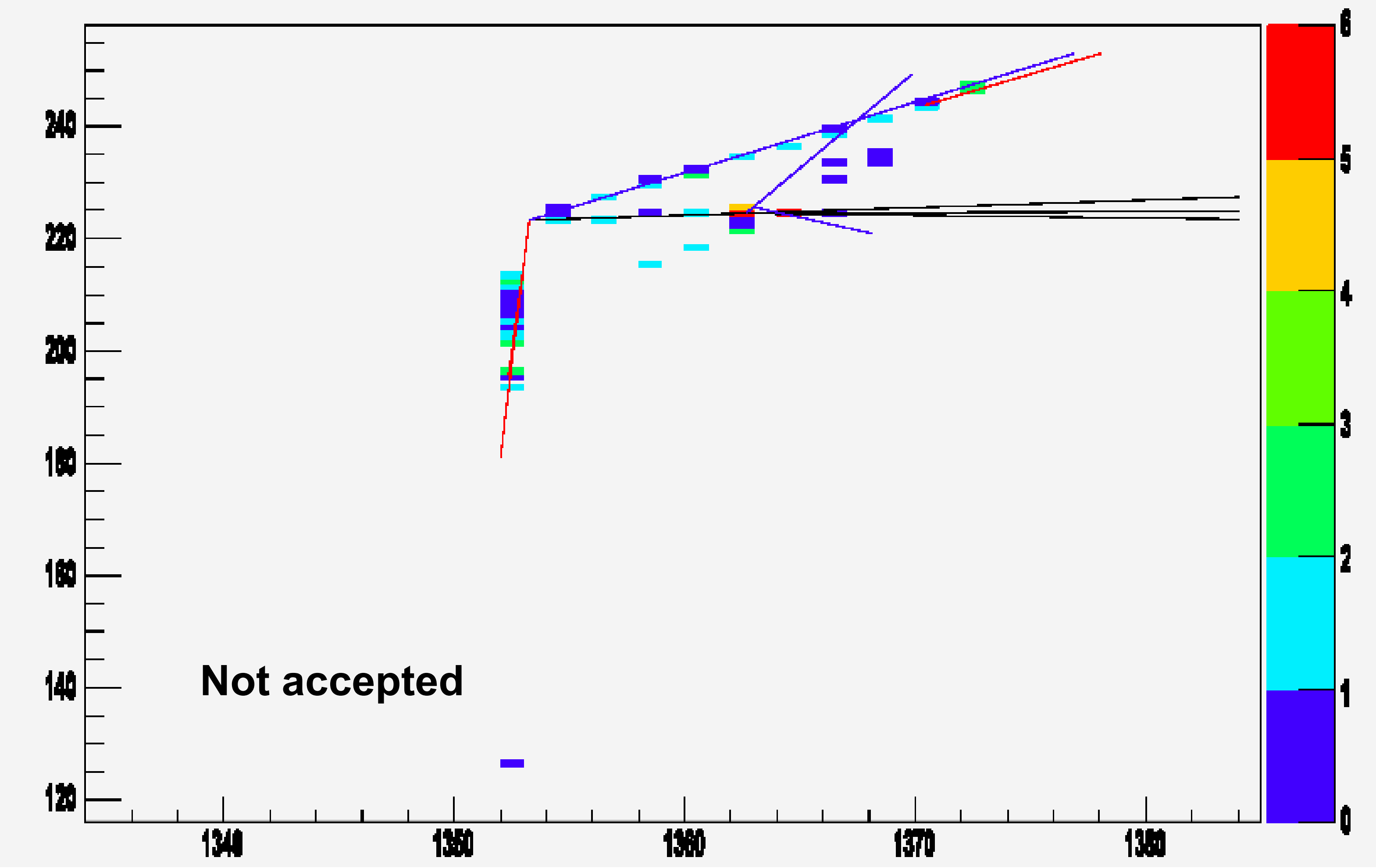
1.87 GeV $\nu_e N \rightarrow e p \pi^+ \pi^0$
x-z View



2.11 GeV $\nu_\mu N \rightarrow \nu_\mu p \pi^0$
x-z View



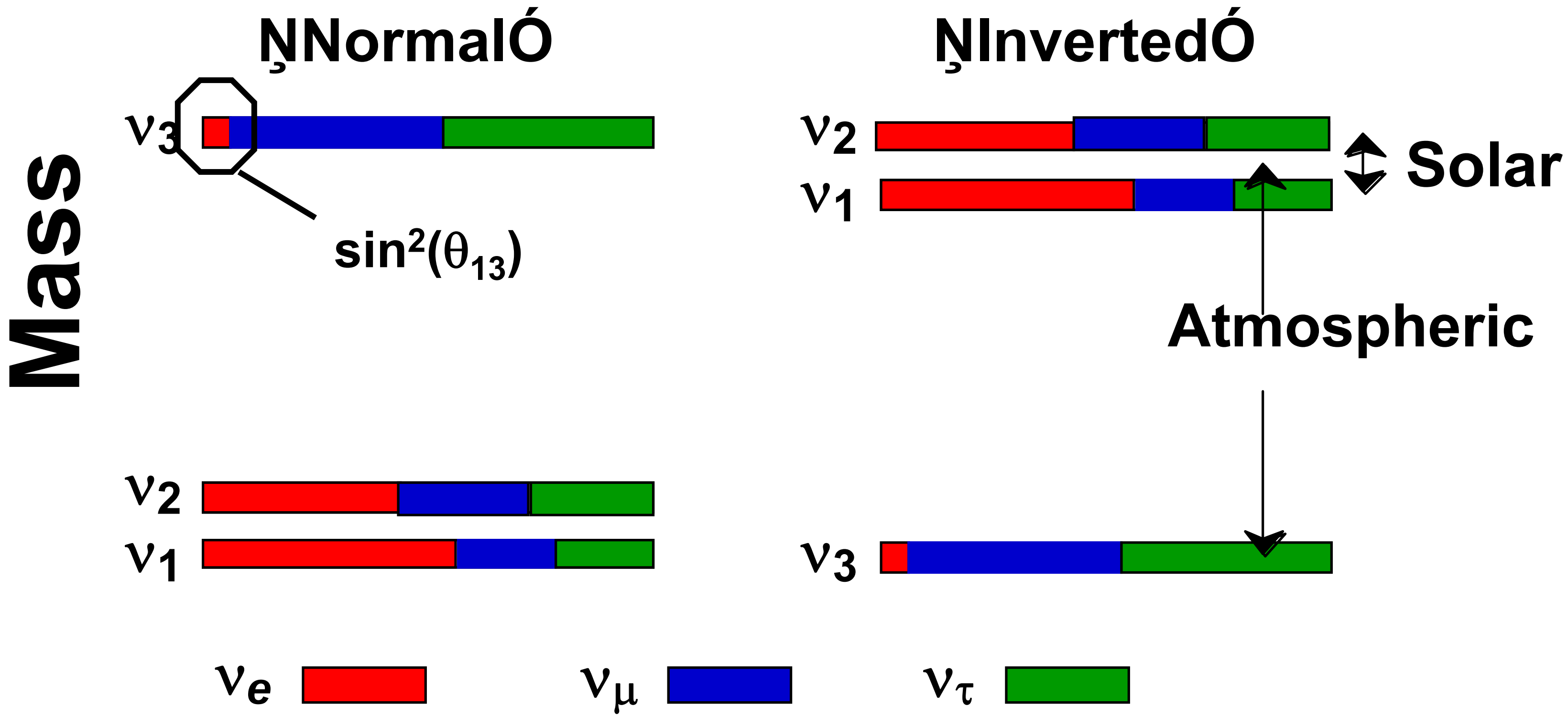
1.86 GeV $\nu_e N \rightarrow ep\pi^+$
x-z View



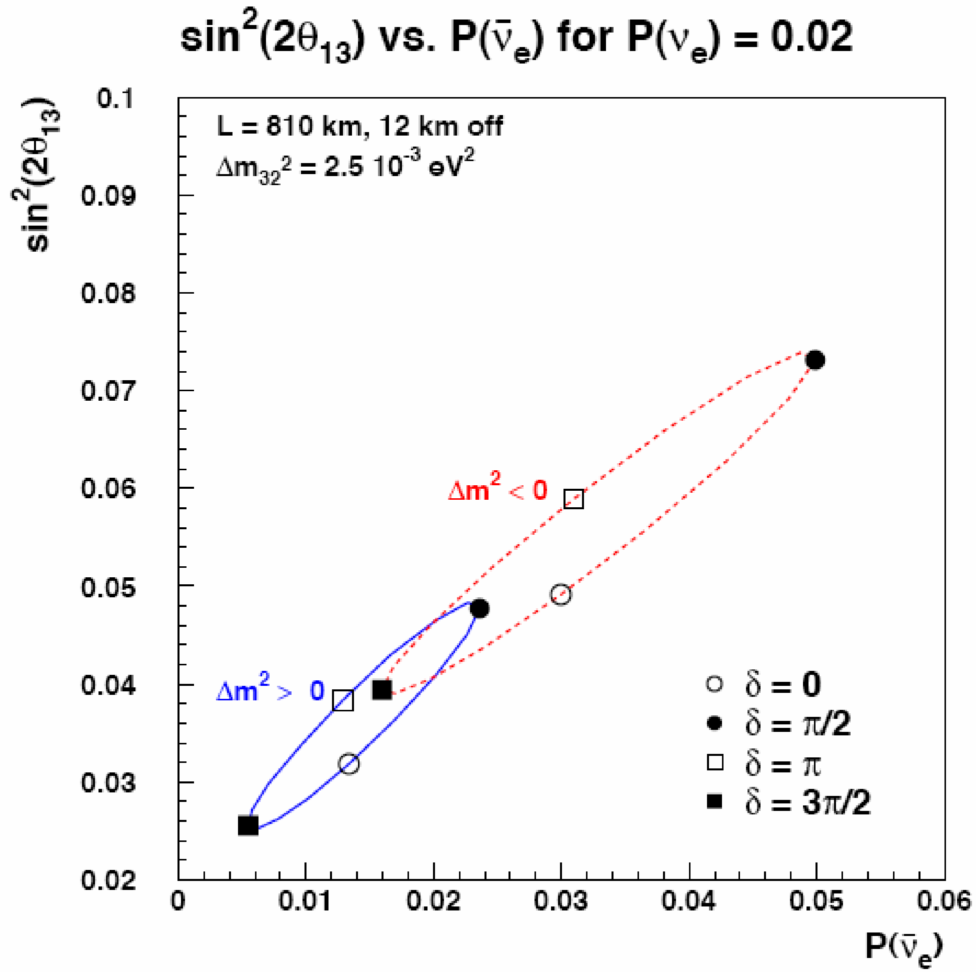
Post-Collider Proton Plan

- **Proton Plan with Collider**
  - **9/11 Slip-stacked Booster batches at 5.5×10^{12} p/batch**
  - **Repetition rate = 0.8 s (Booster) + 1.4 s (Ramp) = 2.2 s**
  - **10% for Collider shot setup + 5% for antiproton transfer**
  - **$\Rightarrow$ 3.4 $\times10^{20}$ protons/yr**
- **Post-Collider Proton Plan**
  - **11 batches for neutrinos $\Rightarrow$ 11/9 = 1.22 factor**
  - **Hide Booster filling time in Recycler $\Rightarrow$ 0.8 s $\rightarrow$ 0.067 s $\Rightarrow$ 2.2 s $\rightarrow$ 1.467 s = 1.50 factor**
  - **Save 10% shot setup and 5% antiproton transfer = 1.17 factor**
  - **$\Rightarrow$ (3.4 $\times10^{20}$ protons/yr)(1.22)(1.50)(1.17) = (7.3 $\times10^{20}$ protons/yr)**
- **Negotiated rate is 90% of this: (6.5$\times10^{20}$ protons/yr)**
- **Proton Driver rate taken as 25$\times10^{20}$ protons/yr**

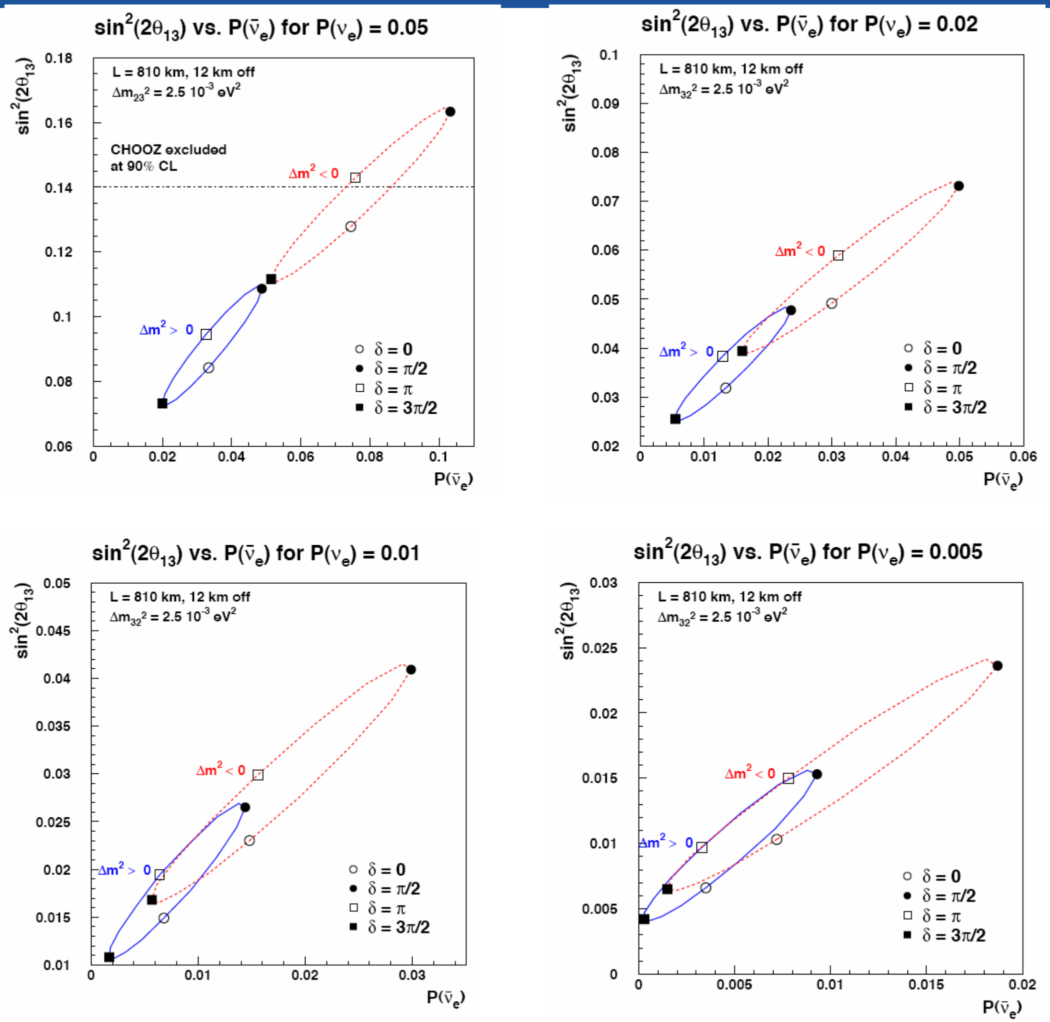
What Do We Know?



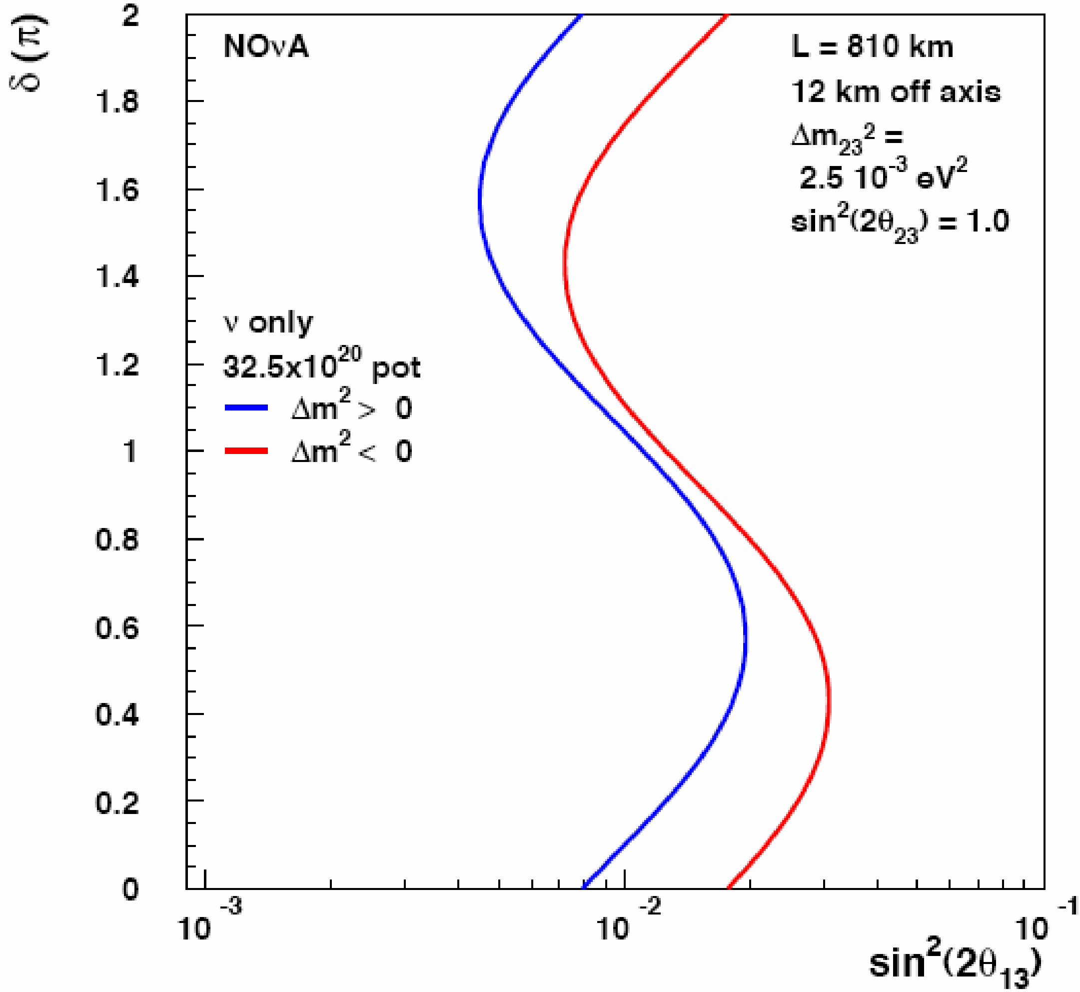
Parameters Consistent with a 2% $\nu_\mu \to \nu_e$ Oscillation



Parameters Consistent with Other Oscillation Probabilities



3 σ Sensitivity to $\theta_{13} \neq 0$



5 year ν only run

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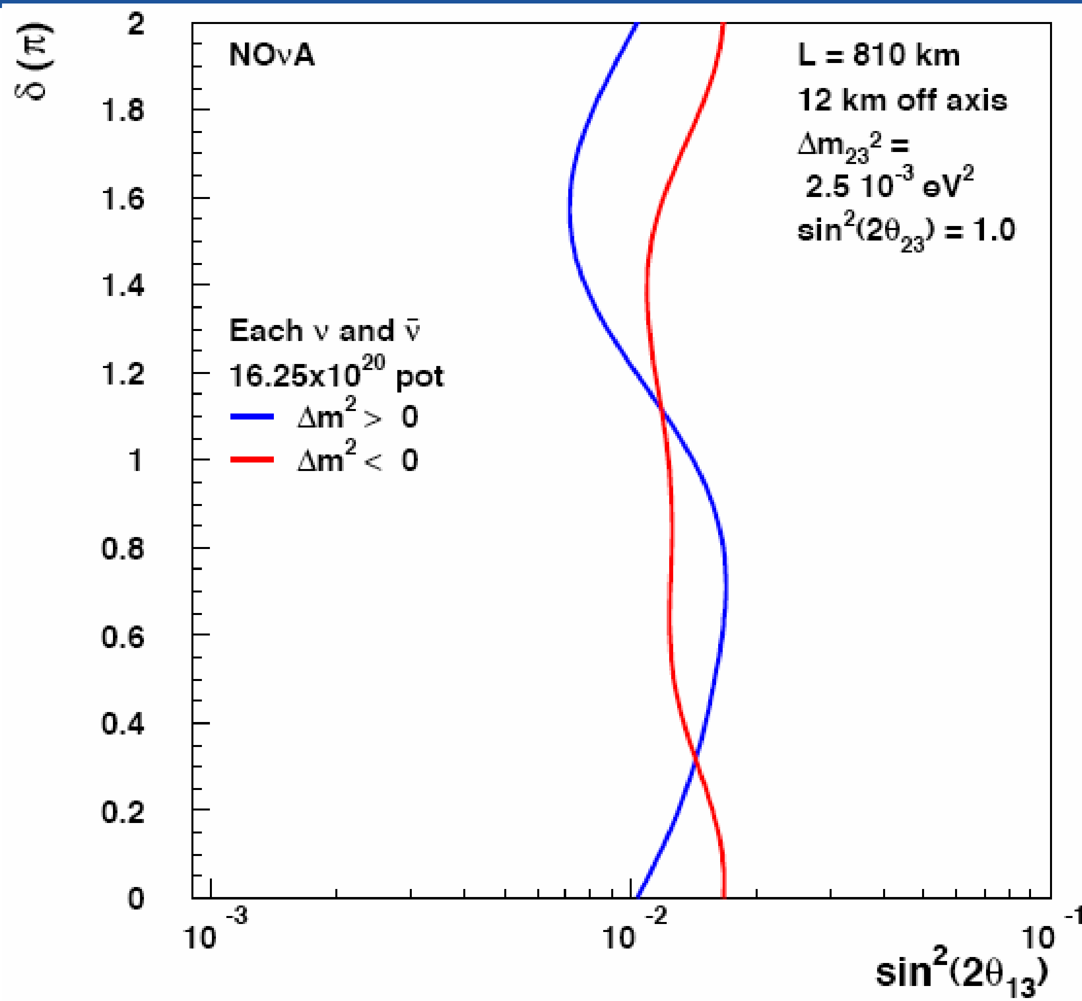
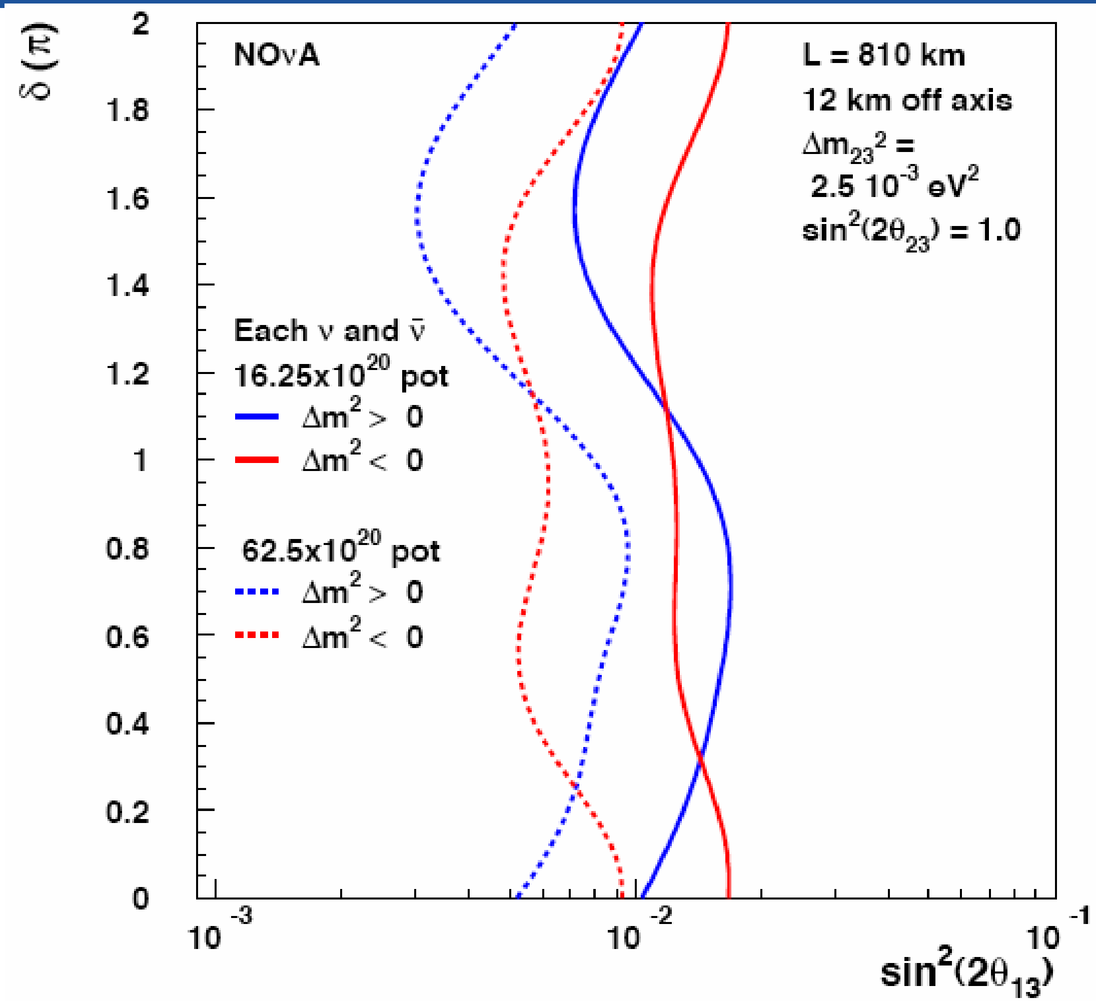


2.5 yr each

ν and $\bar{\nu}$ run

3 σ Sensitivity to $\theta_{13} \neq 0$
Comparison with Proton Driver



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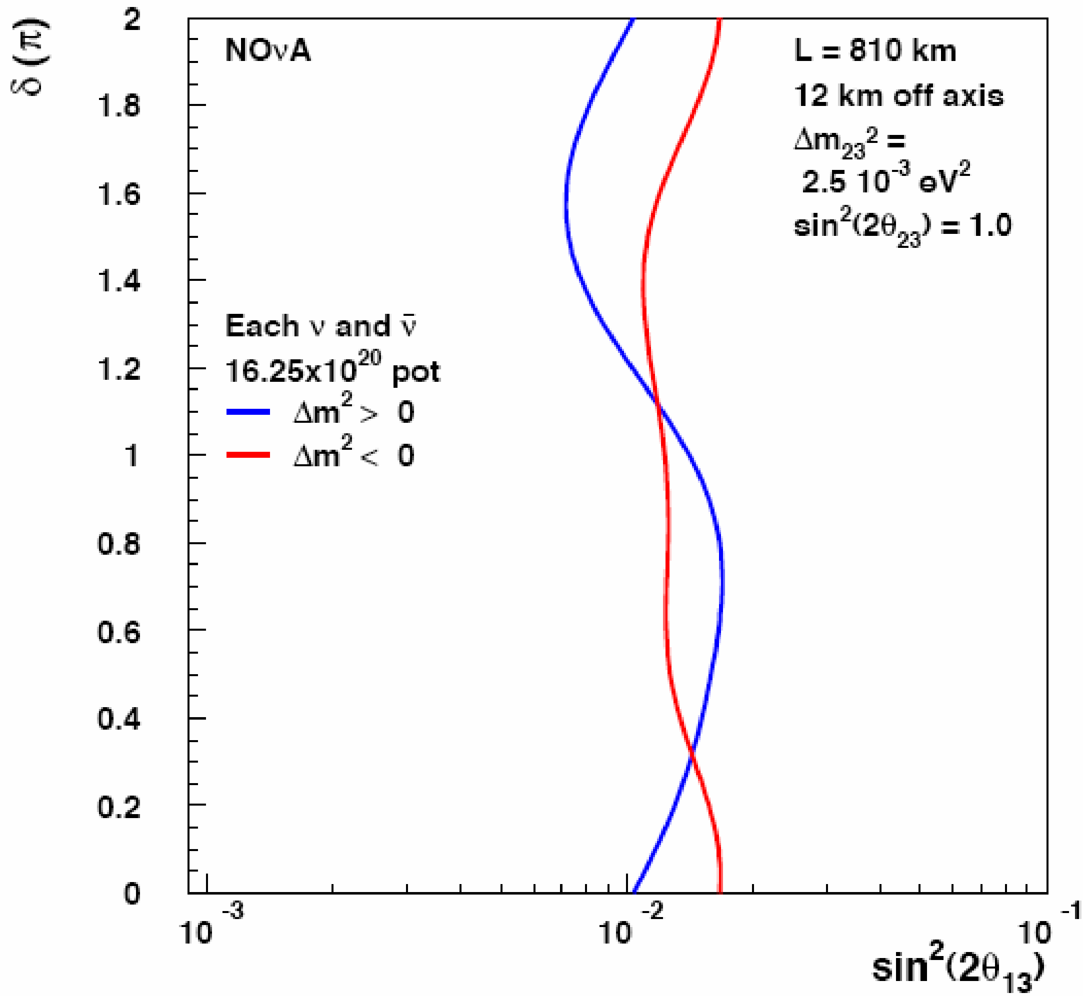

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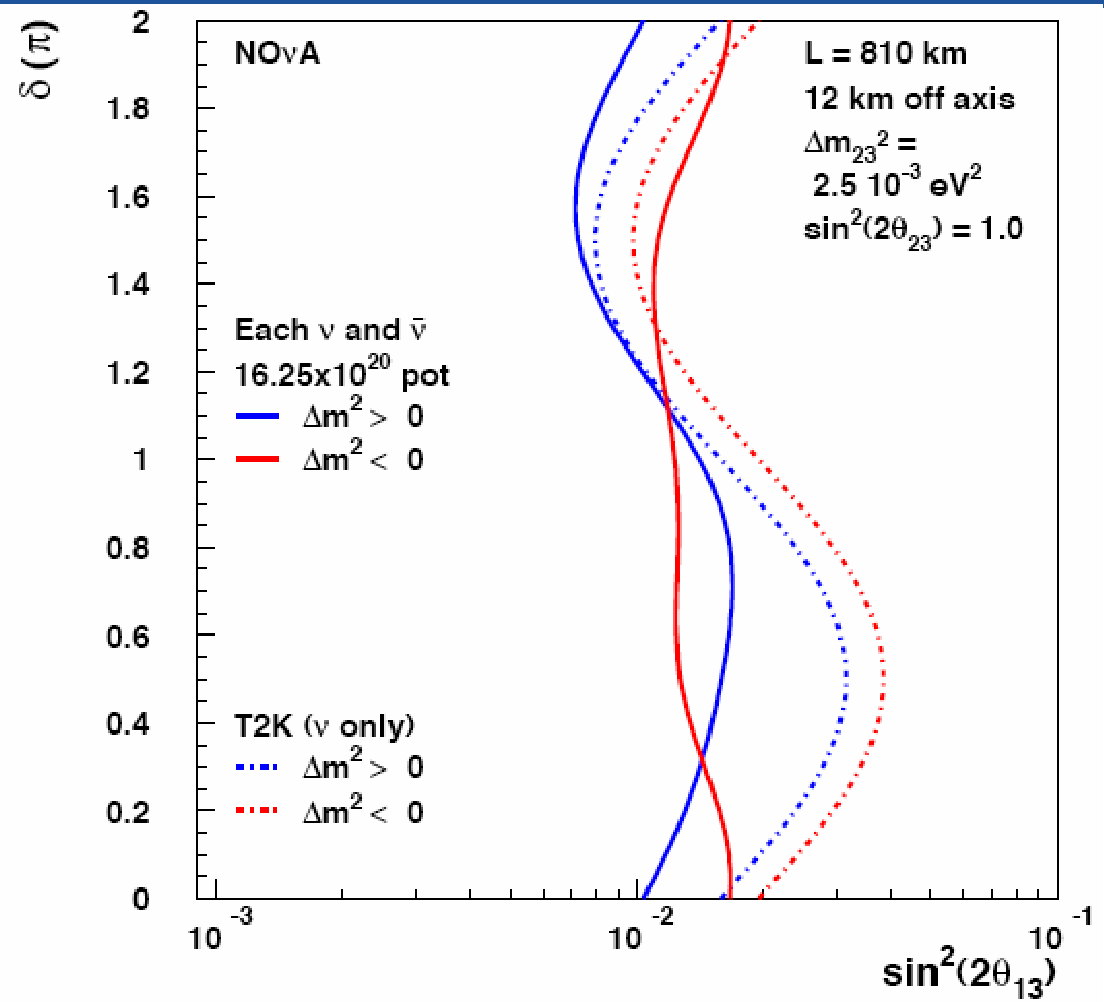

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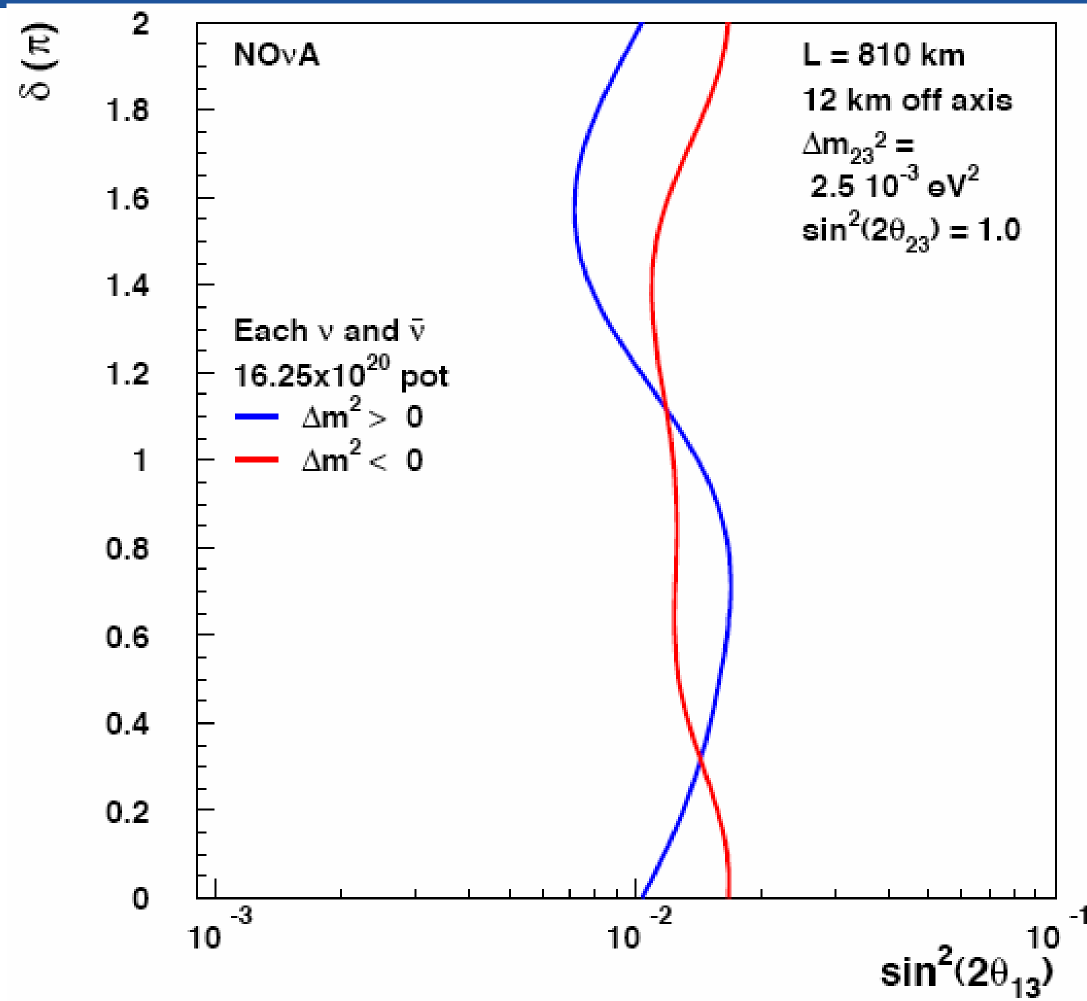

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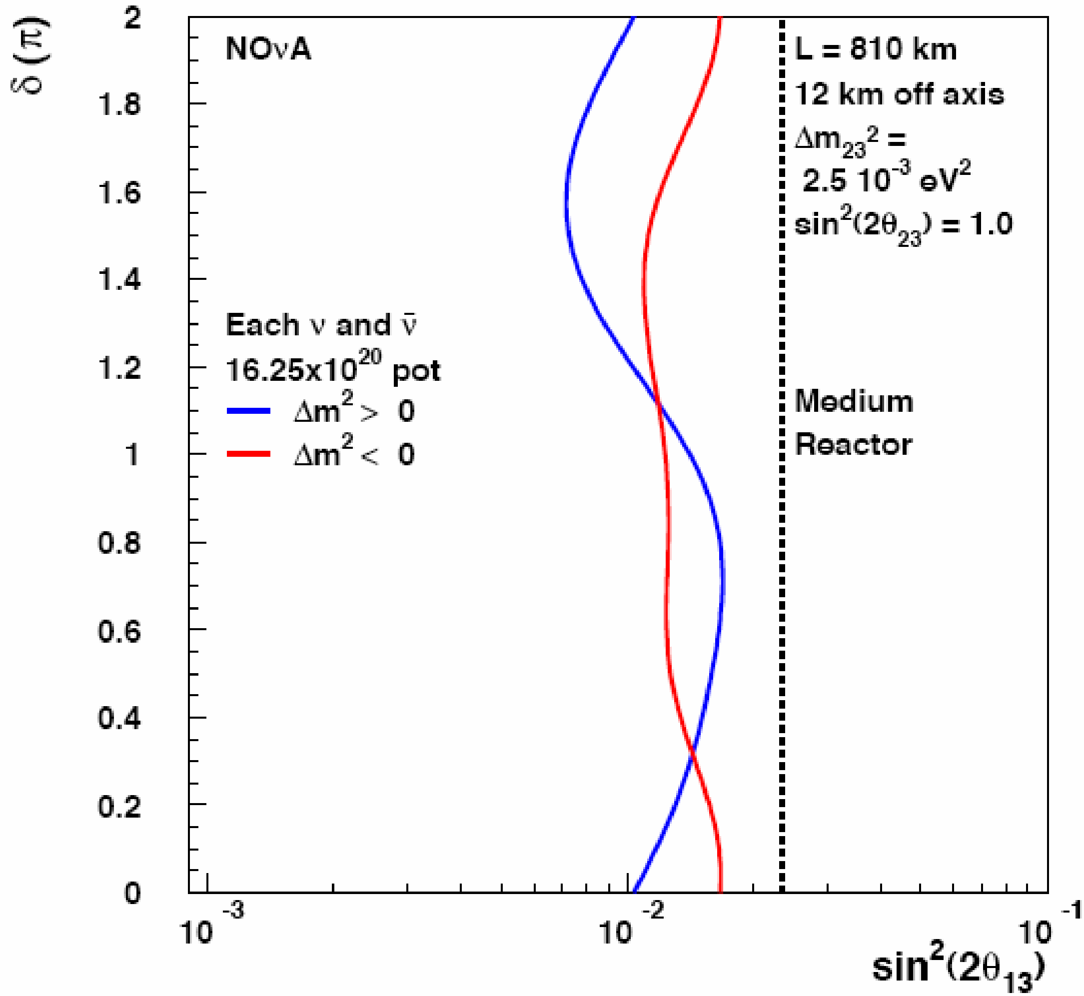

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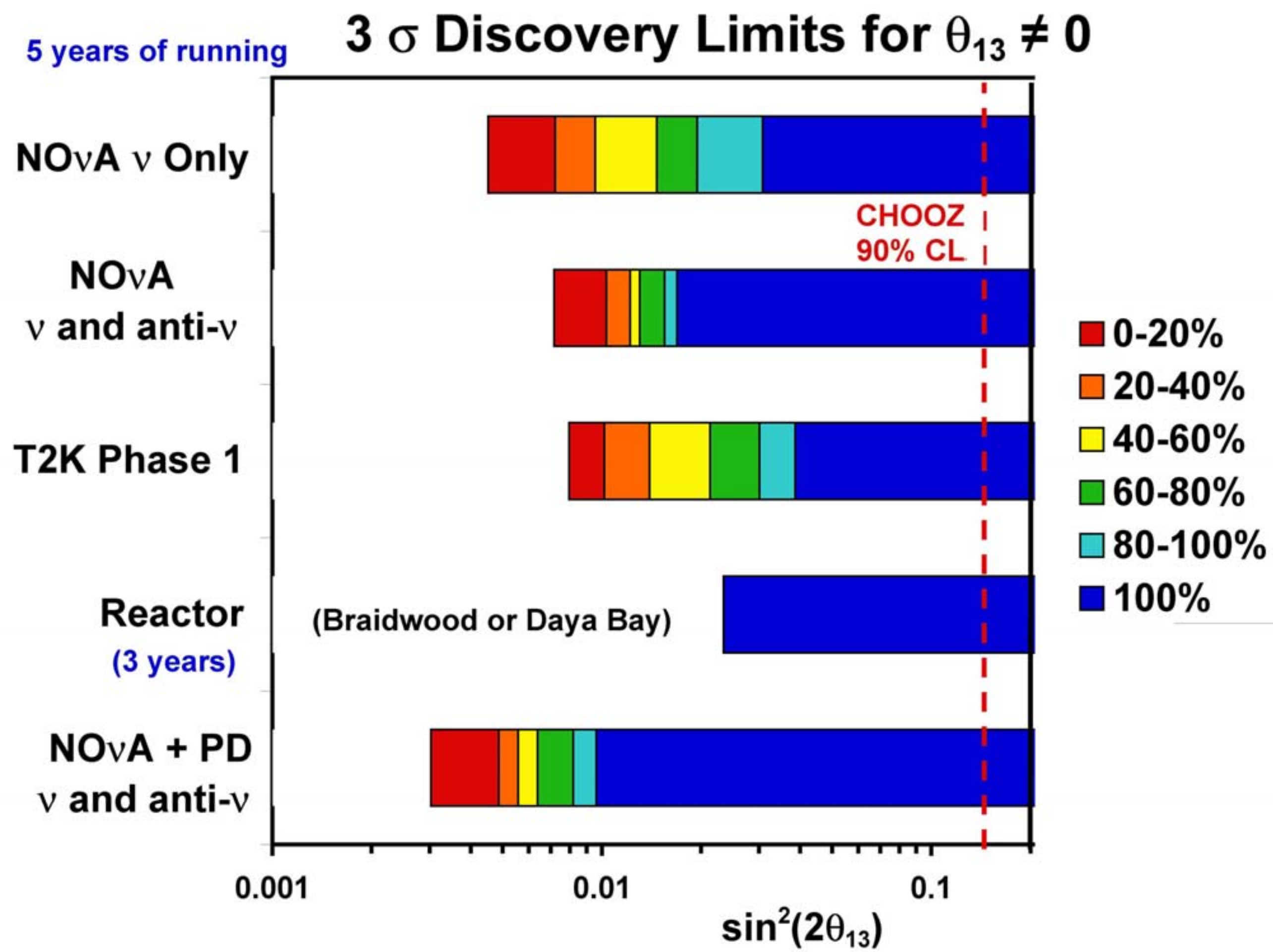


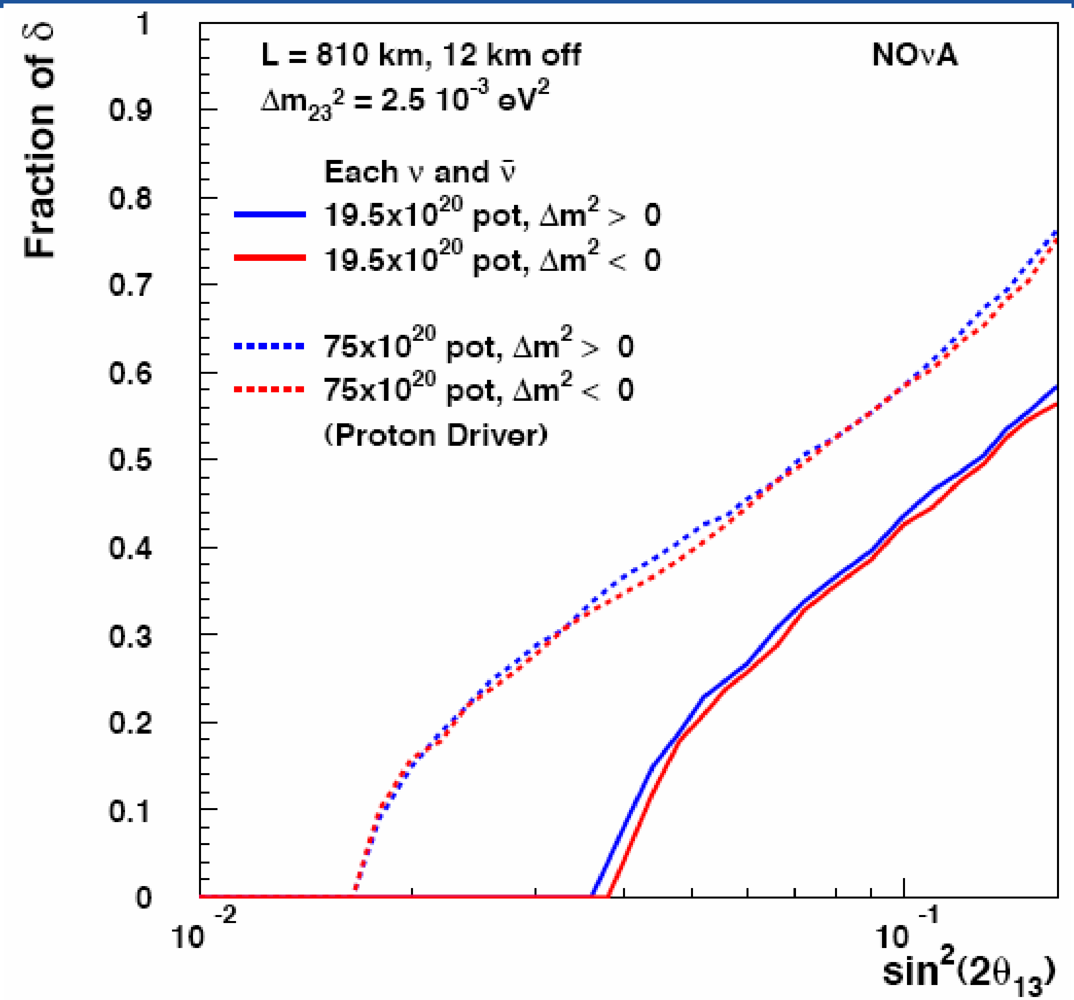
Importance of the Mass Ordering

- Window on very high energy scales: grand unified theories favor the normal mass ordering, but other approaches favor the inverted ordering.
- If we establish the inverted ordering, then the next generation of neutrinoless double beta decay experiment can decide whether the neutrino is its own antiparticle. However, if the normal ordering is established, a negative result from these experiments will be inconclusive.
- To measure CP violation, we need to resolve the mass ordering, since it contributes an apparent CP violation that we must correct for.

Role of NOνA in Resolving the Mass Ordering

- The mass ordering can be resolved only by matter effects in the earth over long baselines.
- NOνA is the only proposed experiment with a sufficiently long baseline to resolve the mass ordering.
- The siting of NOνA is optimized for this measurement.
- NOνA is the first step in a step-by-step program that can resolve the mass ordering in the region accessible to conventional neutrino beams.

95% CL Resolution of the Mass Ordering



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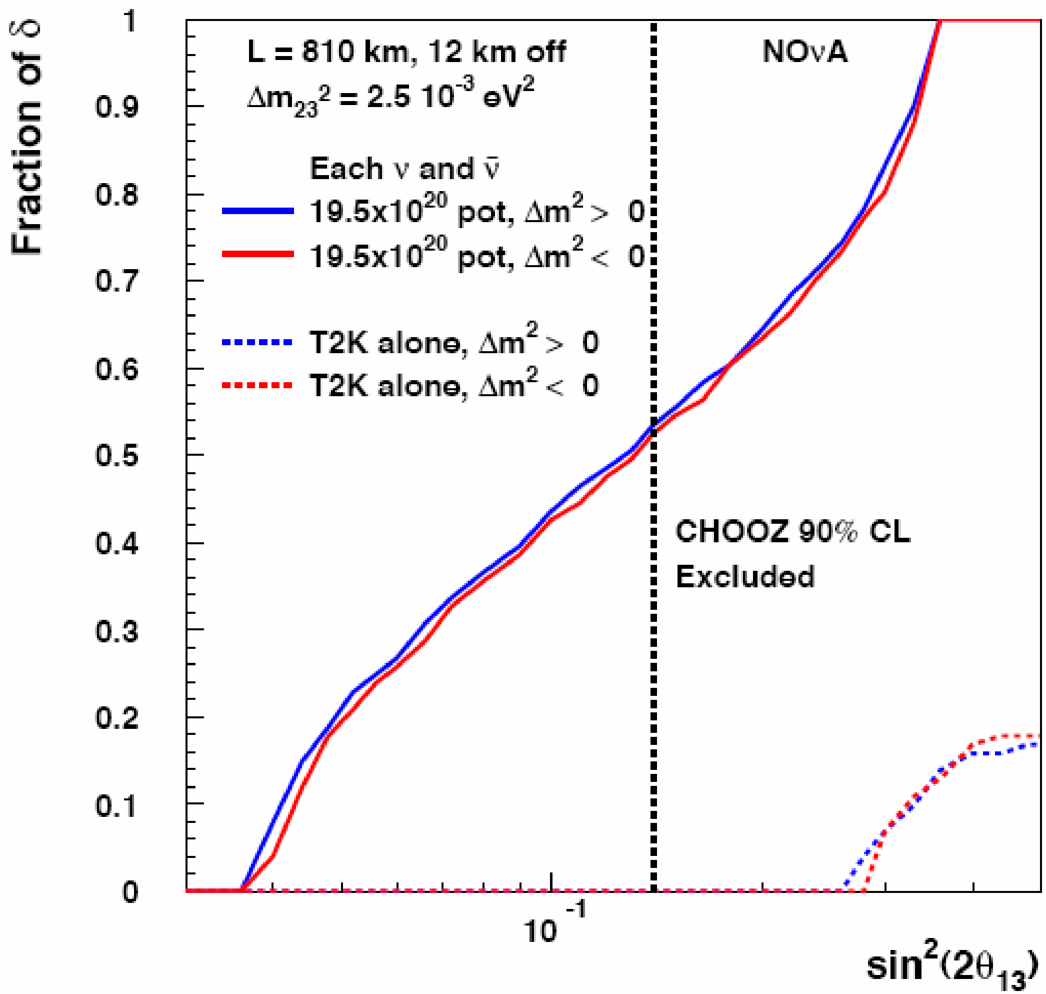

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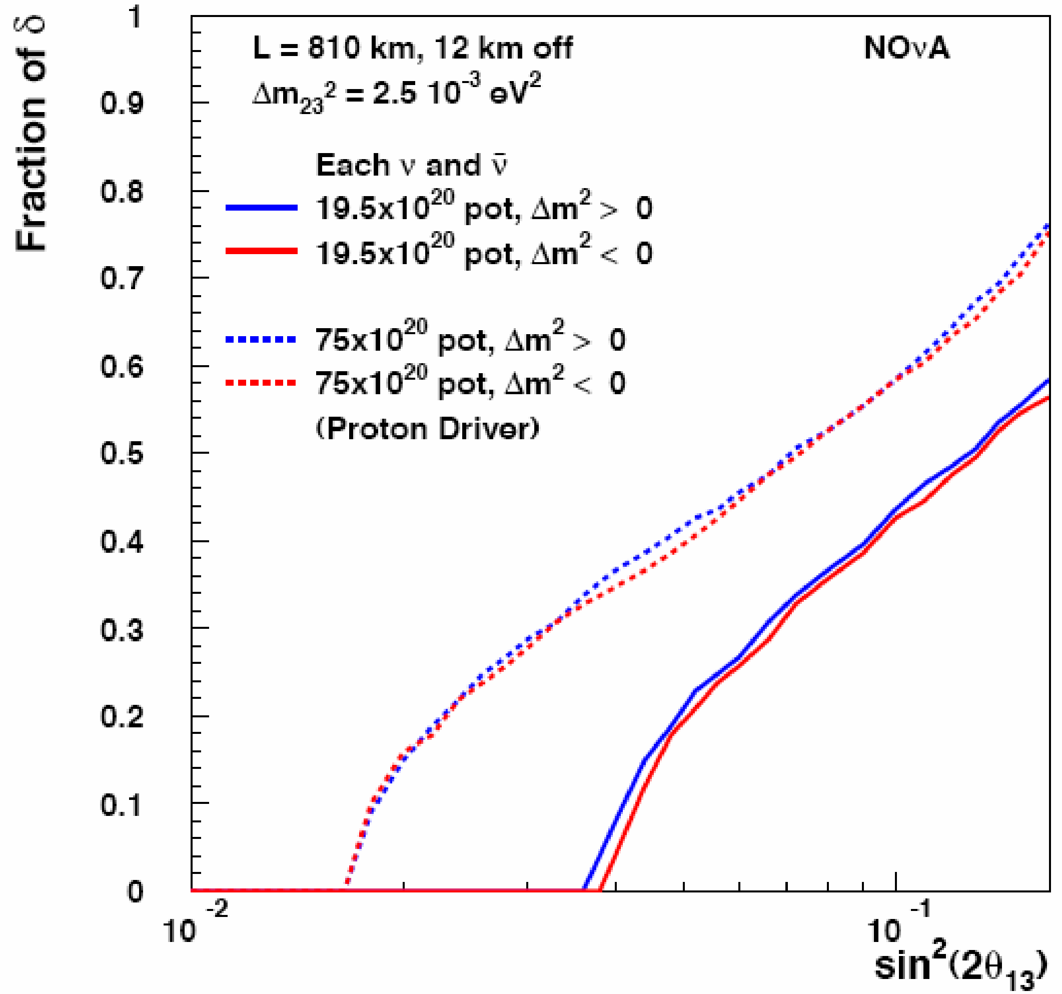

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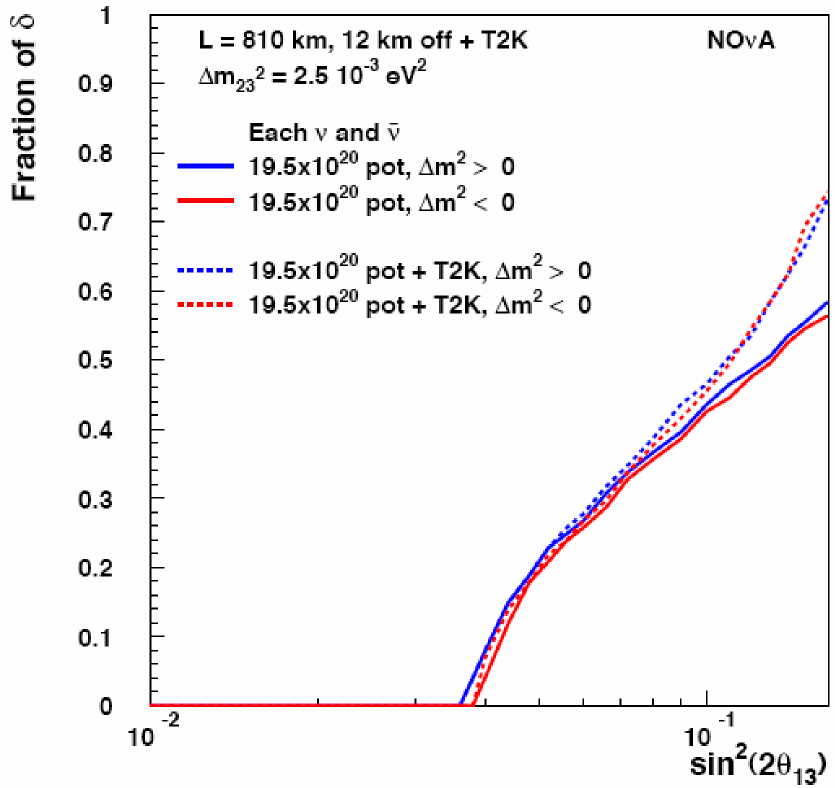
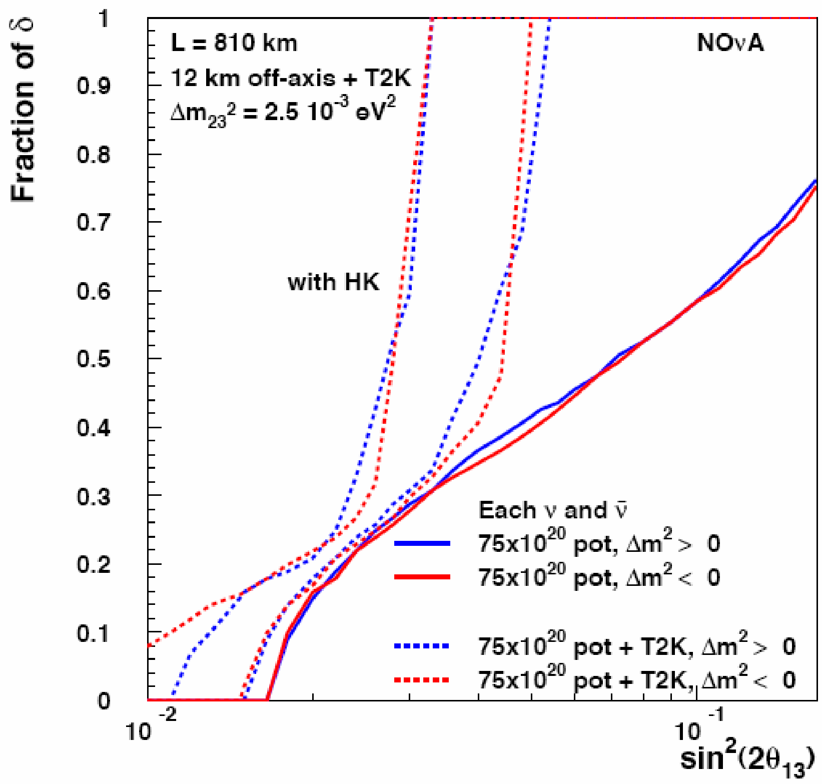
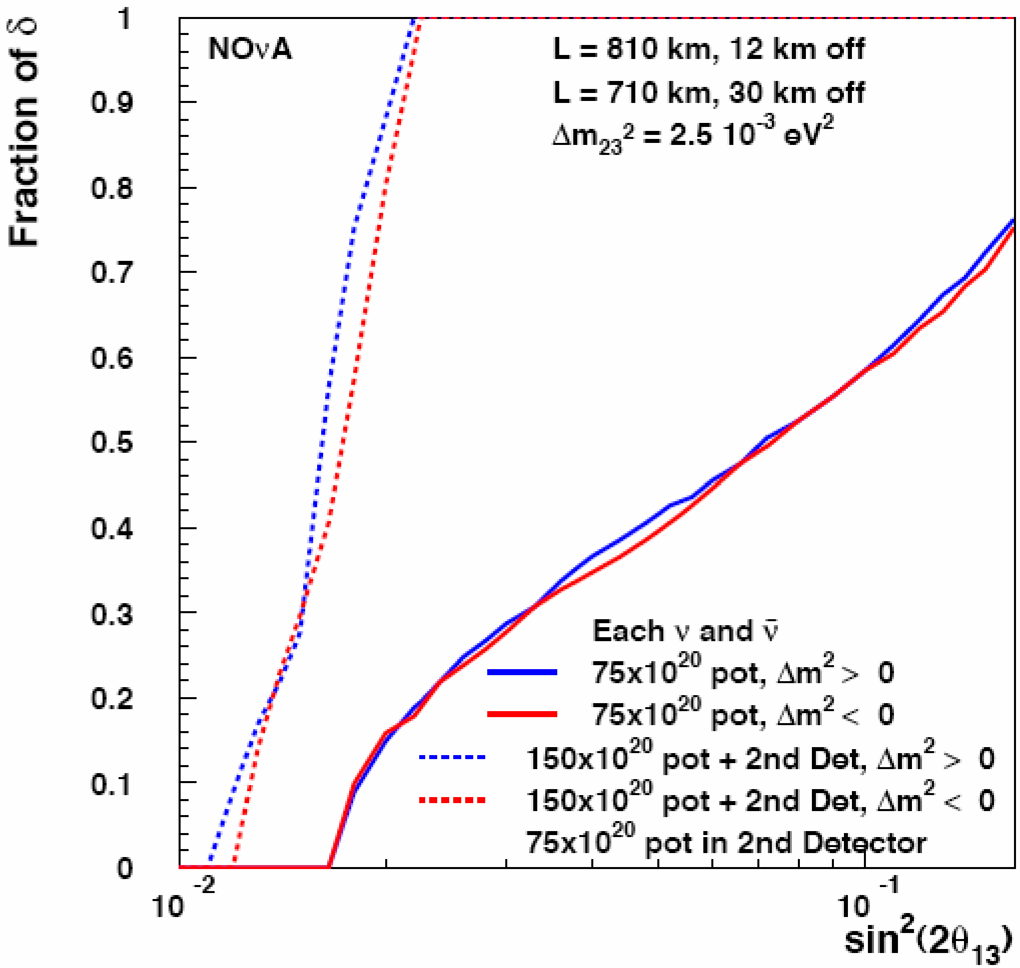


NOνA with T2K Phase 1



NOνA/PD with T2K Phase 2

95% CL Resolution of the Mass Ordering

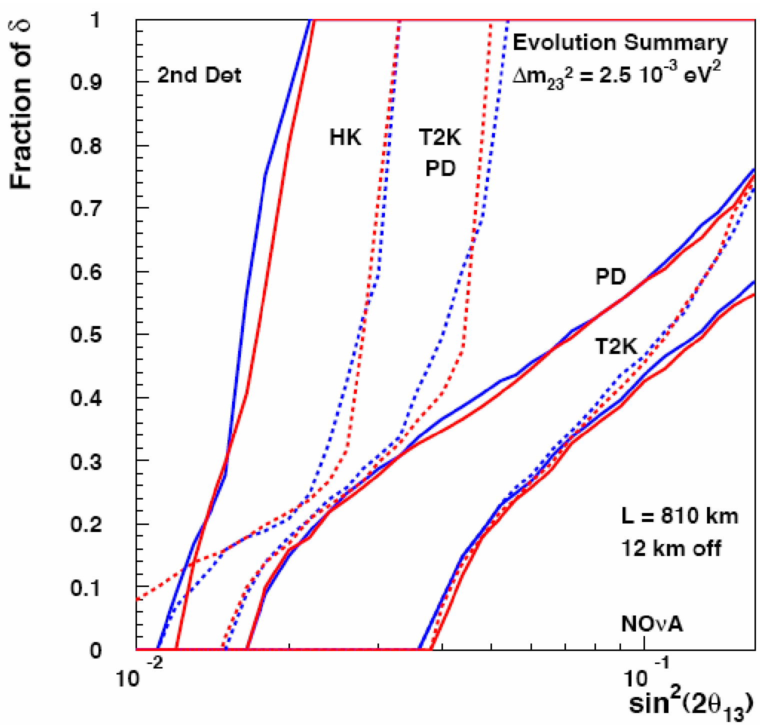


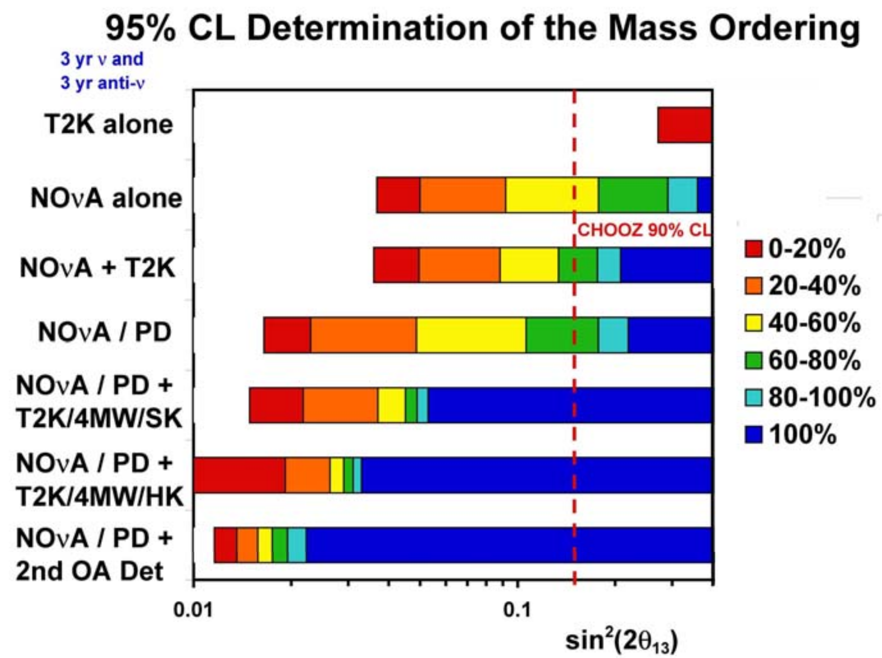
Scenario:

2 years into the PD run, realize the need for the 2nd off-axis detector. Build in 4 years, run for 6 years. Thus, 12 years running of NOνA with PD and 6 years of running the second detector.

Several technologies possible for the 2nd detector. Use SK as a model for the calculation.

95% CL Resolution of the Mass Ordering: Summary





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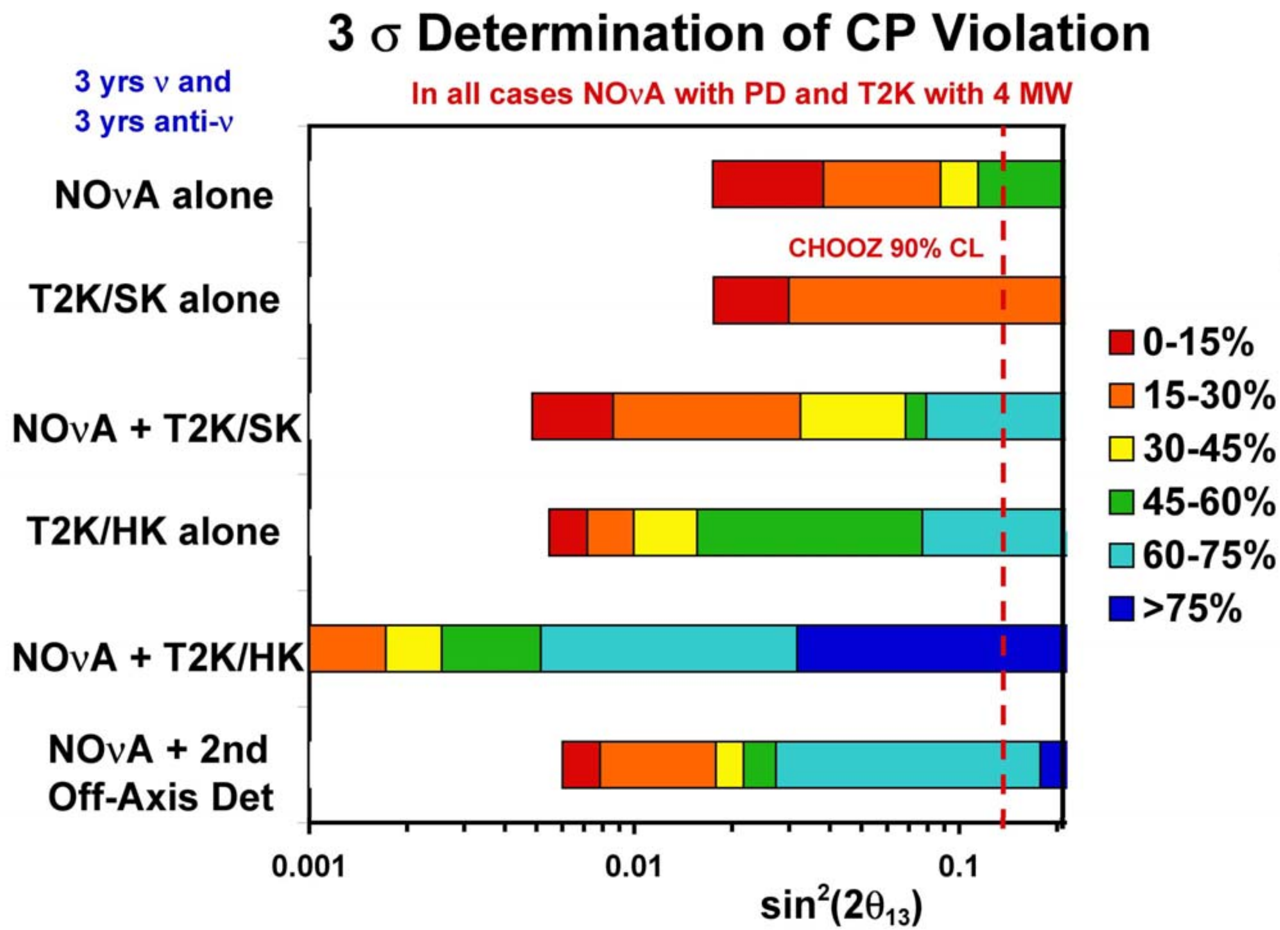
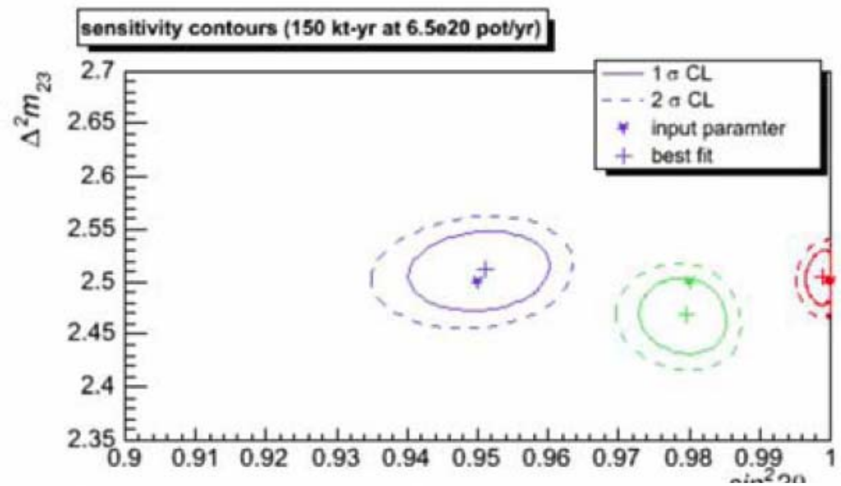
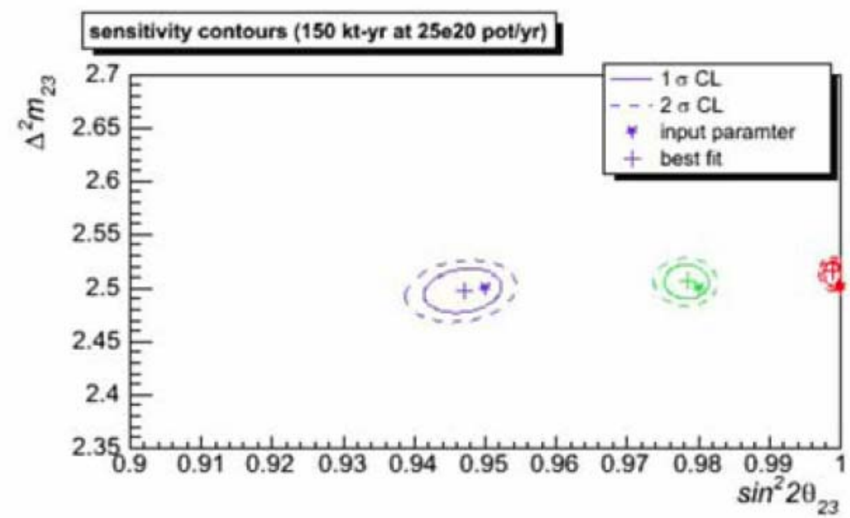


Measurement of Δm_{32}^2 and $\sin^2(2\theta_{23})$

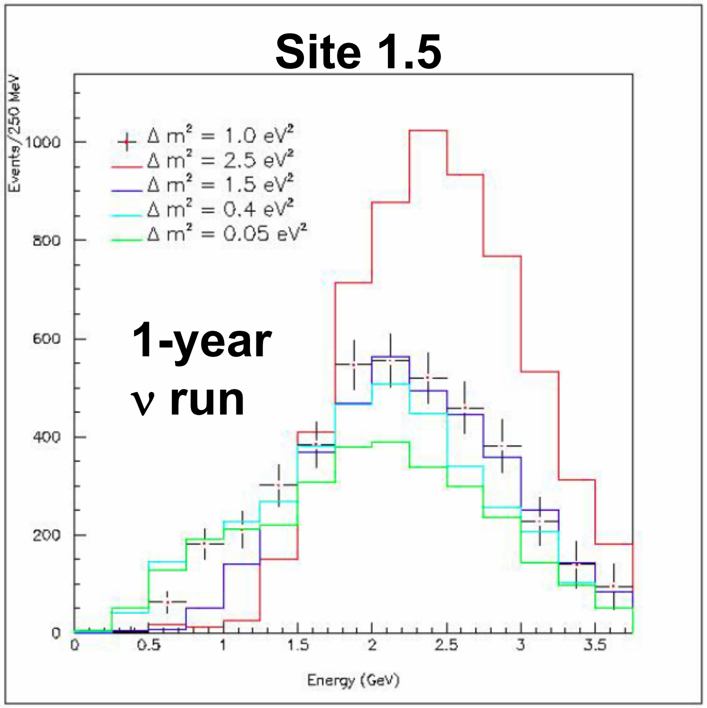


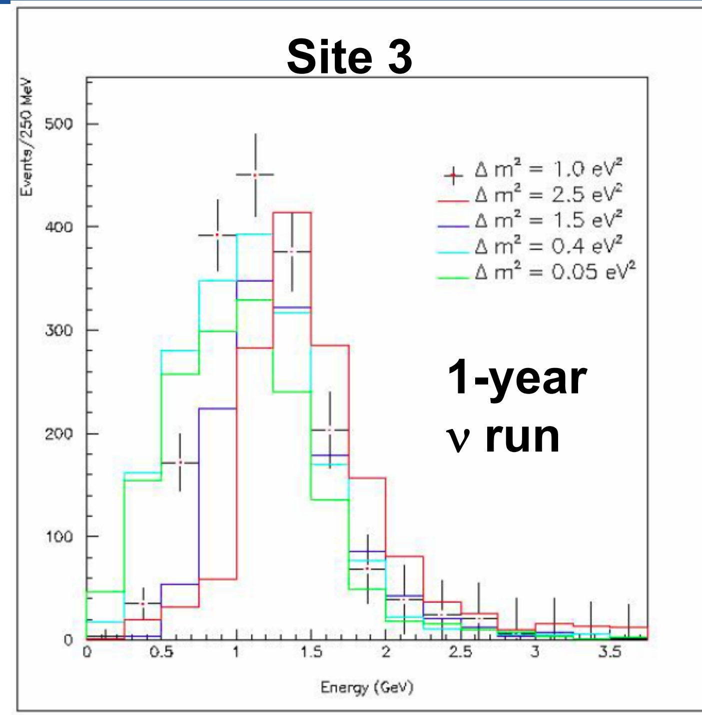
5-year ν run

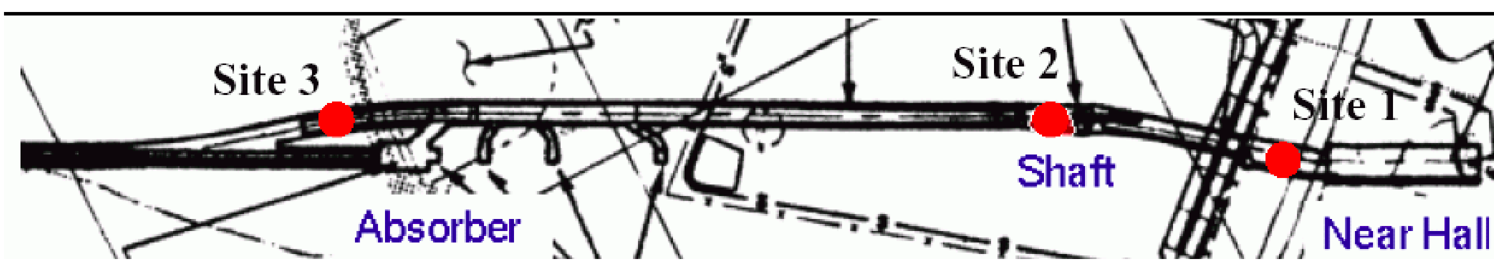


5-year ν run
with Proton Driver

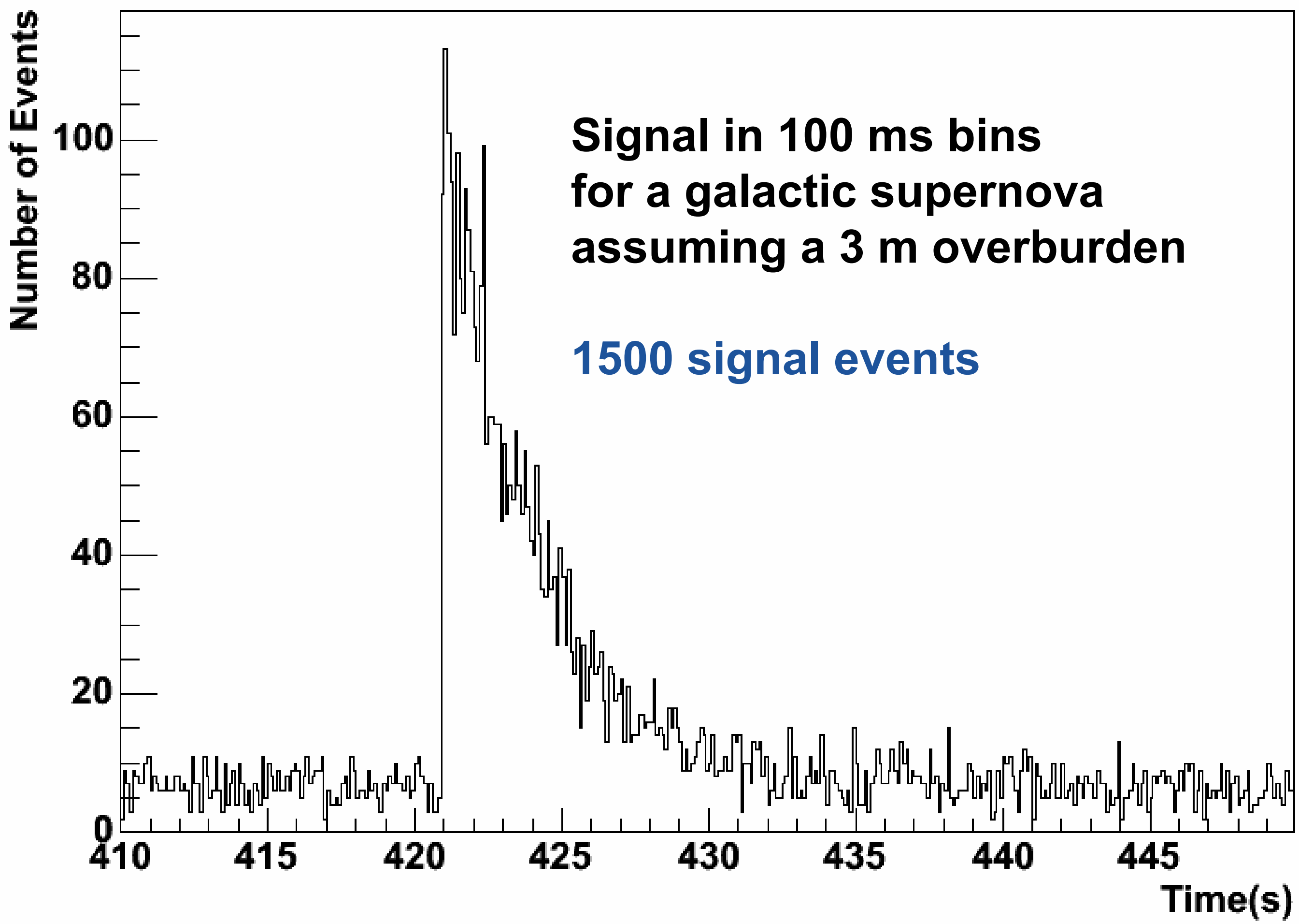
Study MiniBooNE Signal







Sensitivity to a Galactic Supernova



Cost

	Contingency	Total Cost M$
Far Detector		
Active detector	30%	79.5
Electronics and DAQ	55%	13.4
Shipping	21%	7.0
Installation	43%	13.5
Near Detector	44%	3.1
Building and outfitting	58%	29.3
Project management	25%	4.7
Additional contingency		14.1
Total	50%	164.7

Schedule (10 of 29 Milestones)

Project start	Oct 2006
R&D prototype Near Detector complete	Mar 2007
Start Far Detector Building construction	Jul 2007
Start receiving packaged APDs	Oct 2007
Start extrusion module factories	Oct 2007
Start construction of Near Detector	Dec 2007
Start operation of Near Detector	Jul 2008
Start Far Detector assembly	May 2009
First kiloton operational	Oct 2009
Full 30 kilotons operational	Jul 2011

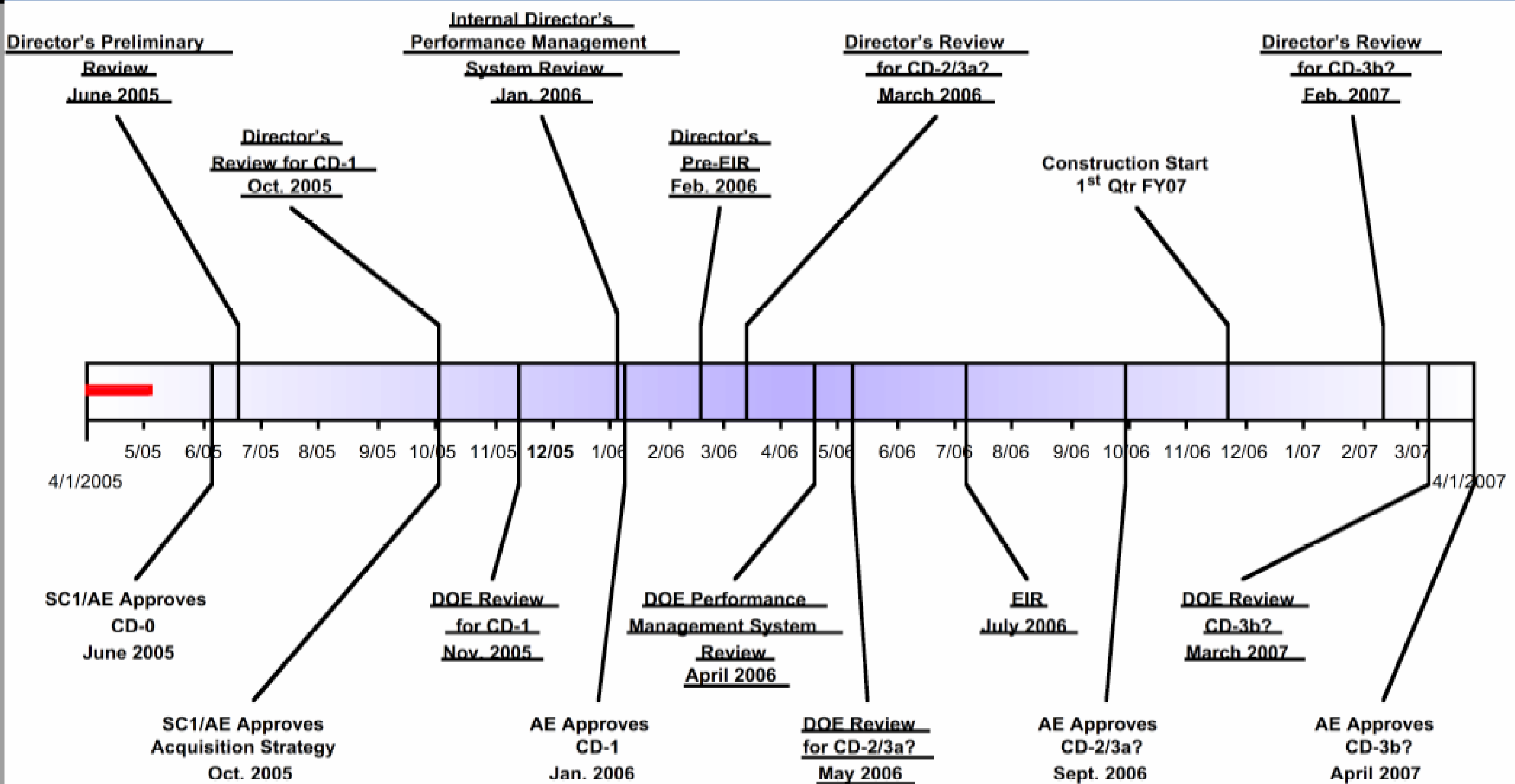
NOνA Status

- Approved by Fermilab April 2005: Letter from Mike Witherell
  - "The Committee found that NOνA …is the best approach to address the compelling neutrino physics questions ahead of us. They judged NOνA to be well designed, fully competitive, and complementary to other efforts. They also consider it to be the right platform for further steps in the evolving neutrino program worldwide. The Committee recommended Stage I approval."
  - "Organizing the best program of neutrino research with Fermilab's accelerators is critical to the strength of the particle physics program in the US and worldwide. I agree with the Committee's judgment that NOνA is the right experiment to anchor this program, and I agree that now is the time to act. I therefore grant Stage I approval to the NOνA experiment."

NOνA Status

- Approved by Fermilab April 2005 (see letter)
- Ed Temple has set out a schedule of critical decisions and reviews that will allow a Oct 2006 construction start (see timeline)

Ed Temple's Timeline of Critical Decisions and Reviews

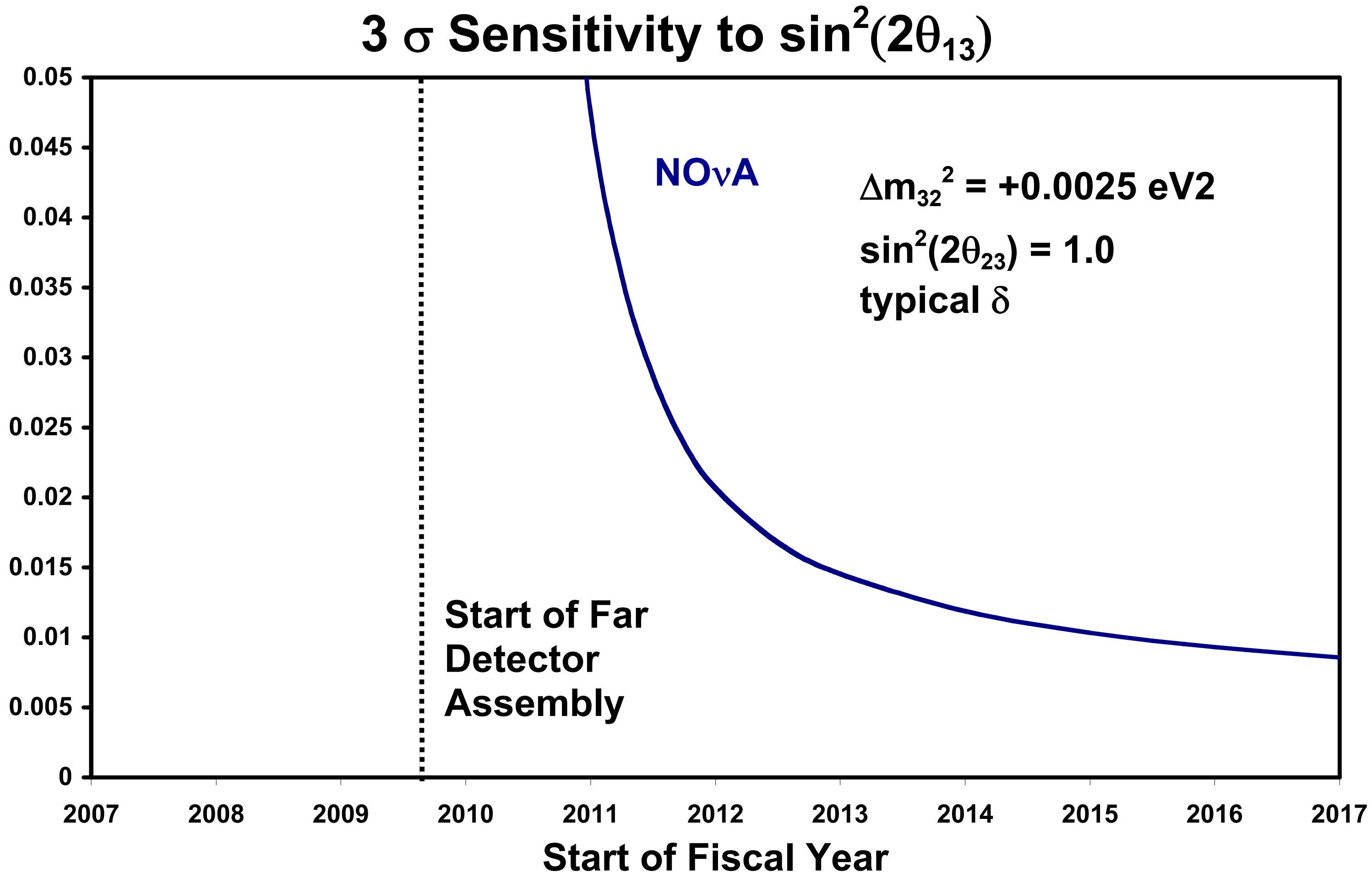


11 reviews in 22 months exclusive of NuSAG, P5, and the PAC

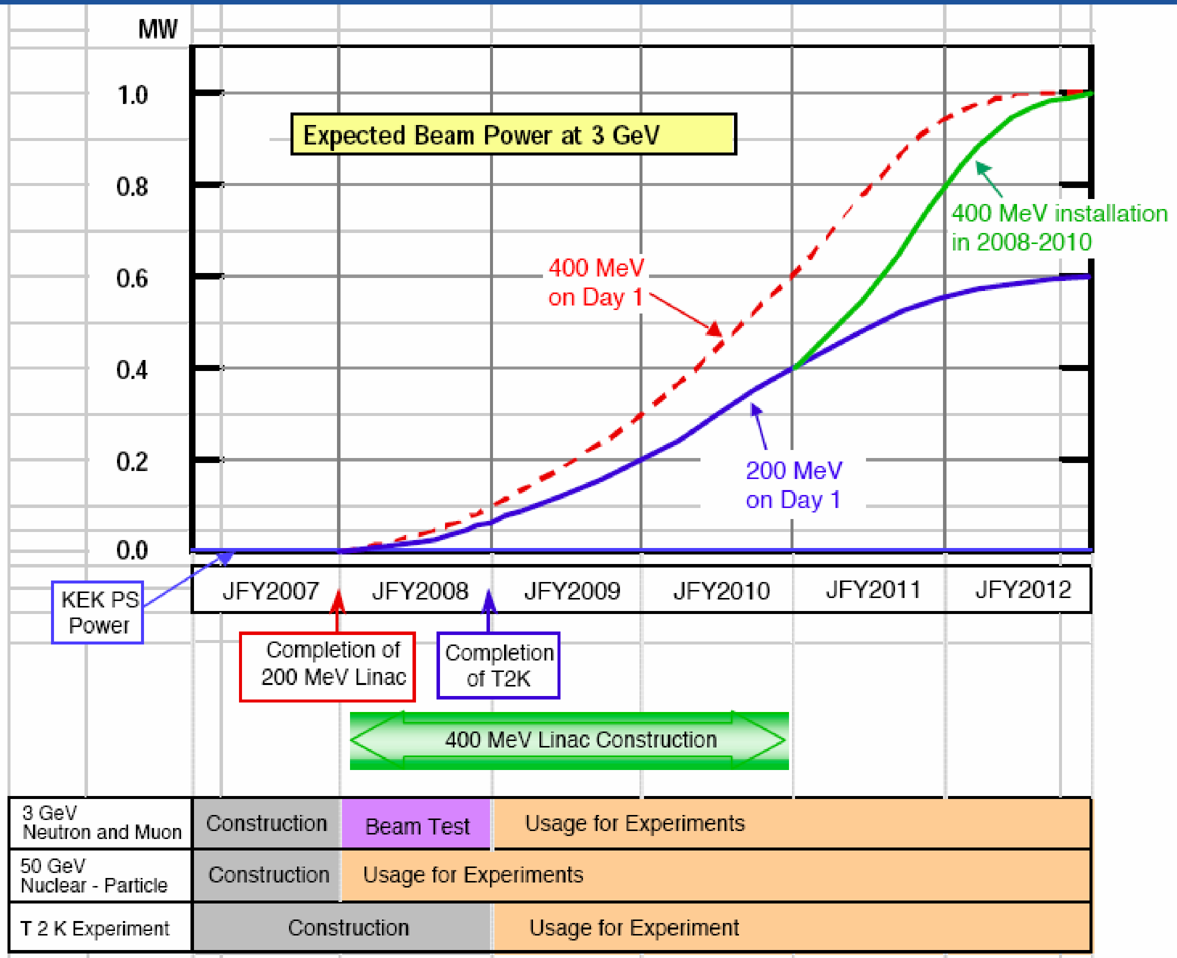
NOνA Status

- Approved by Fermilab April 2005 (see letter)
- Ed Temple has set out a schedule of critical decisions and reviews that will allow a Oct 2006 construction start (see timeline)
- We have started setting up a project management team at Fermilab. NOνA cospokesperson John Cooper will act as Project Manager and Ron Ray will act as Deputy Project Manager. (John will step down as cospokesperson when his term ends in about 9 months.)

Sensitivity vs. Time

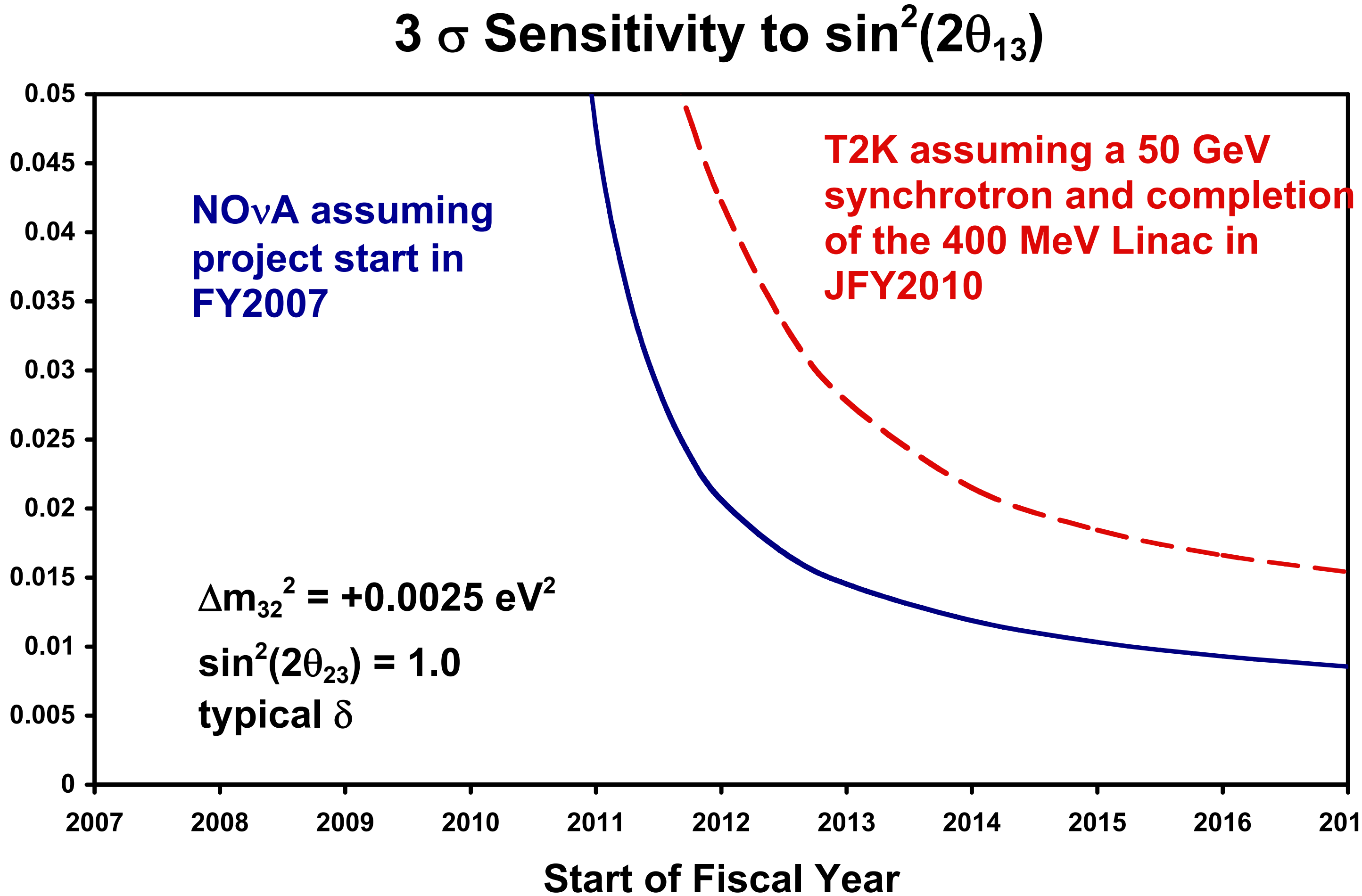


Assumed T2K Beam Power vs. Time

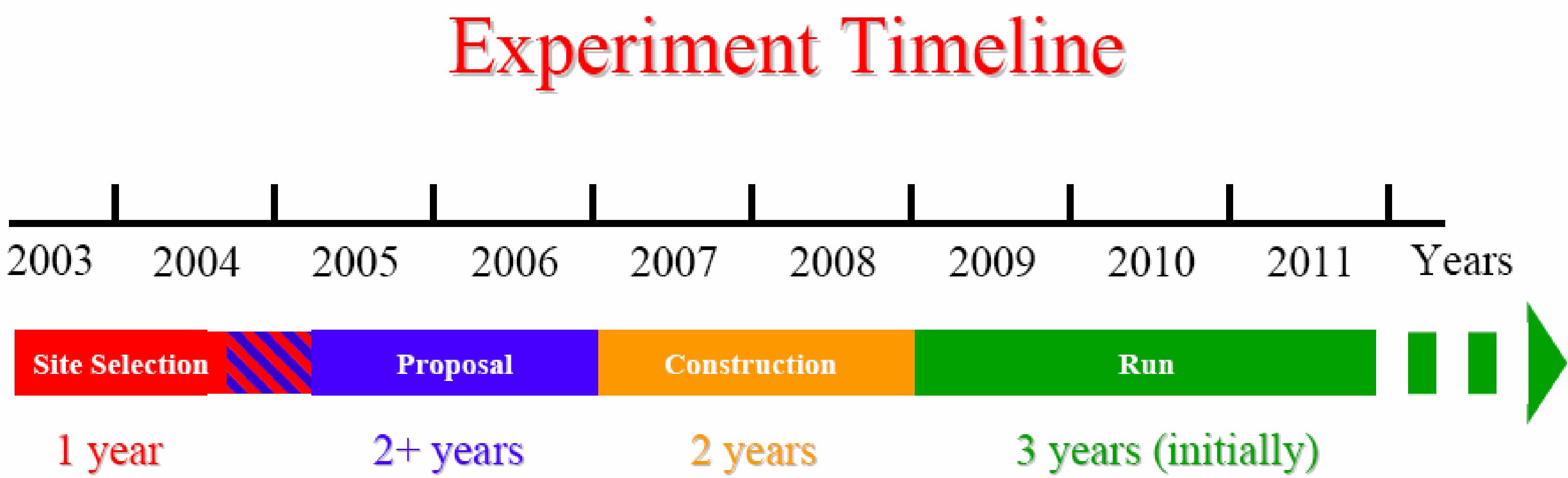


From S. Nagamiya, Feb 2005

Sensitivity vs. Time
Comparison to T2K

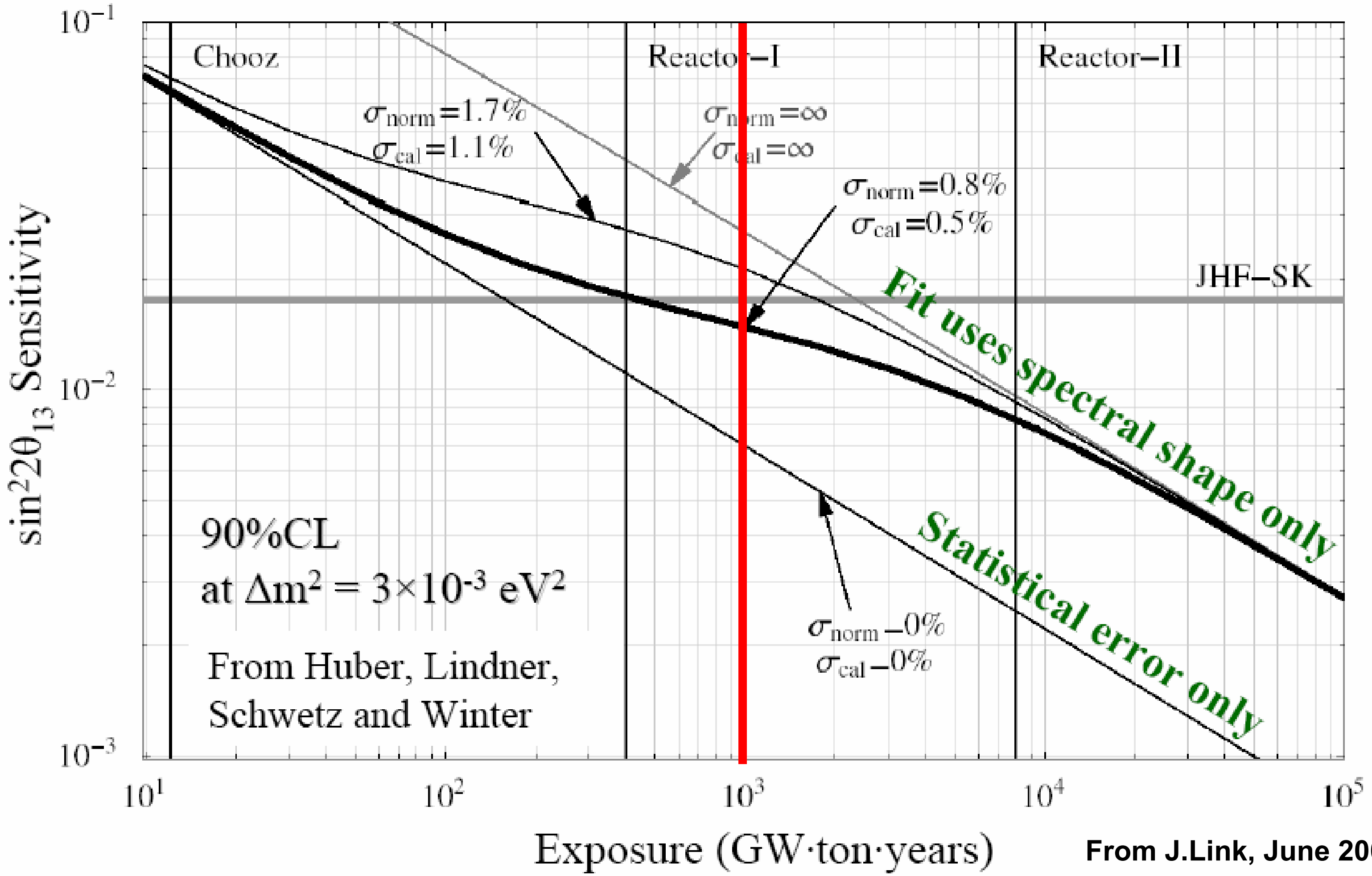


Assumed Reactor Timeline



From J.Link, June 2004

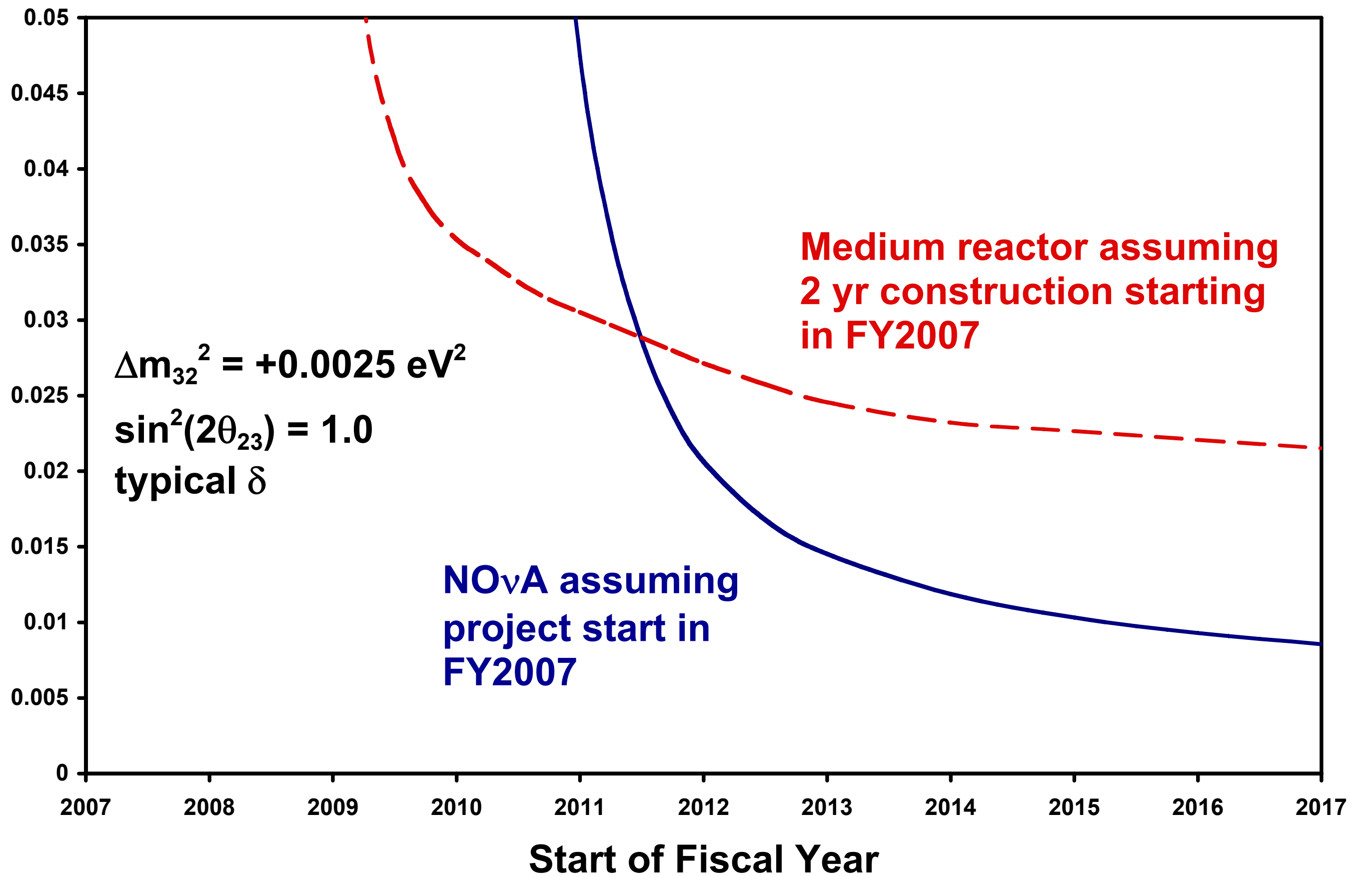
Reactor Sensitivity Model with 900 GW tons/yr



From J.Link, June 2004

Sensitivity vs. Time
Comparison to a reactor experiment

3 σ Sensitivity to $\sin^2(2\theta_{13})$



Conclusion

- **NOνA provides a flexible approach to studying all of the parameters of neutrino oscillations**
  - **A long baseline approach is crucial in the context of the world program.**
  - **NOνA is the first stage of a flexible program where each stage can be planned according to what has been learned in previous stages.**
  - **The NOνA physics reach is greater than other experiments being contemplated for the next few years.**
  - **The full range of the NOνA/NuMI program is comparable to that of other conventional approaches.**
  - **NOνA is the size project that can be started now.**

Backup Slides

$P(\nu_\mu \rightarrow \nu_e)$ (in Vacuum)

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$
  - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$ "Atmospheric"
  - $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$ "Solar"
  - $P_3 = \mp J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$

  $\left.\right\}$ Atmospheric-solar interference

  where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \times$

  $\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$

$P(\nu_\mu \rightarrow \nu_e)$ (in Matter)

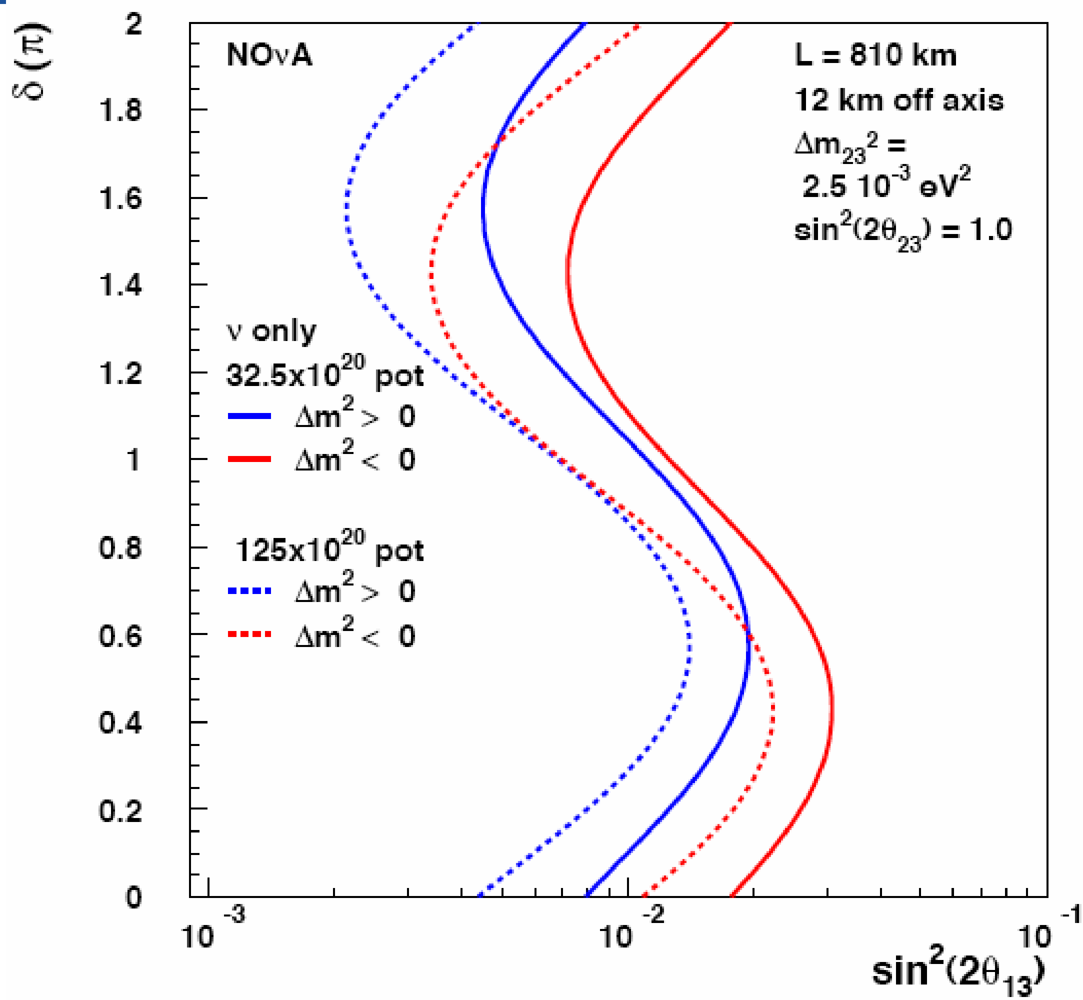
- In matter at oscillation maximum, P_1 will be approximately multiplied by (1 ± $2E/E_R$) and P_3 and P_4 will be approximately multiplied by (1 ± E/E_R), where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

$$E_R = \frac{\Delta m^2_{13}}{2\sqrt{2}G_F\rho_e} \approx 11\,\text{GeV for the earthÕs crust.}$$

About a ±30% effect for NuMI, but only a ±11% effect for JPARC .

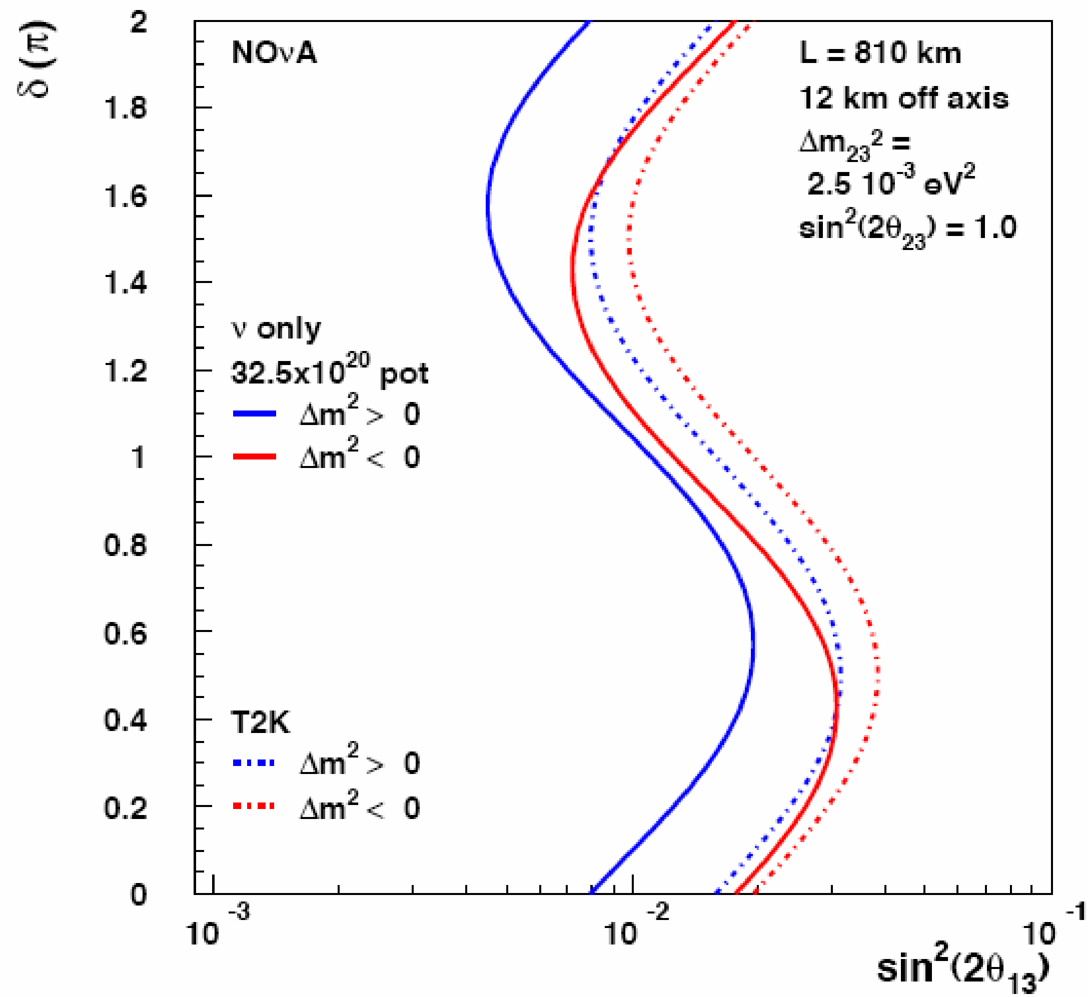
However, the effect is reduced for energies above the oscillation maximum and increased for energies below.

3 σ Sensitivity to $\theta_{13} \neq 0$
Comparison with Proton Driver



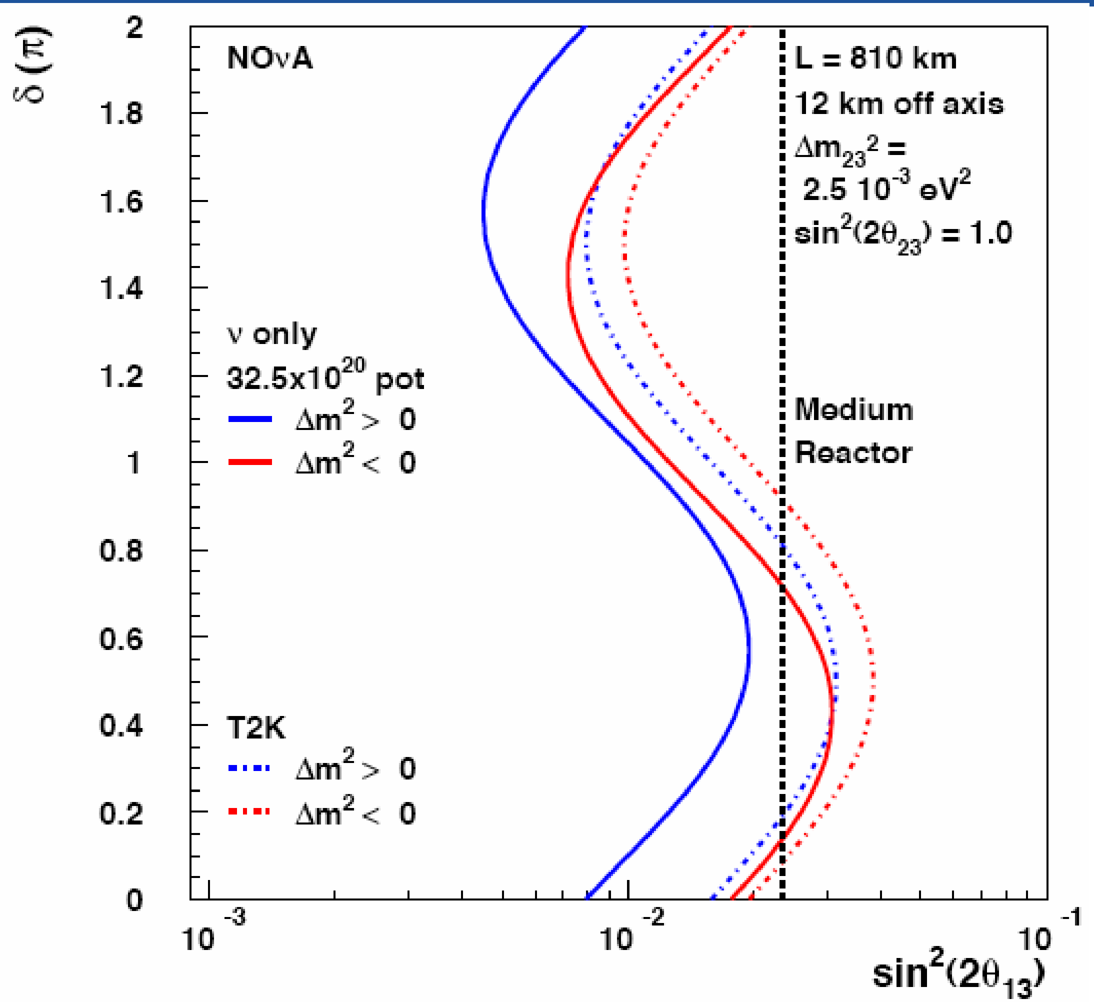
5 year ν only run

3 σ Sensitivity to $\theta_{13} \neq 0$
Comparison with T2K



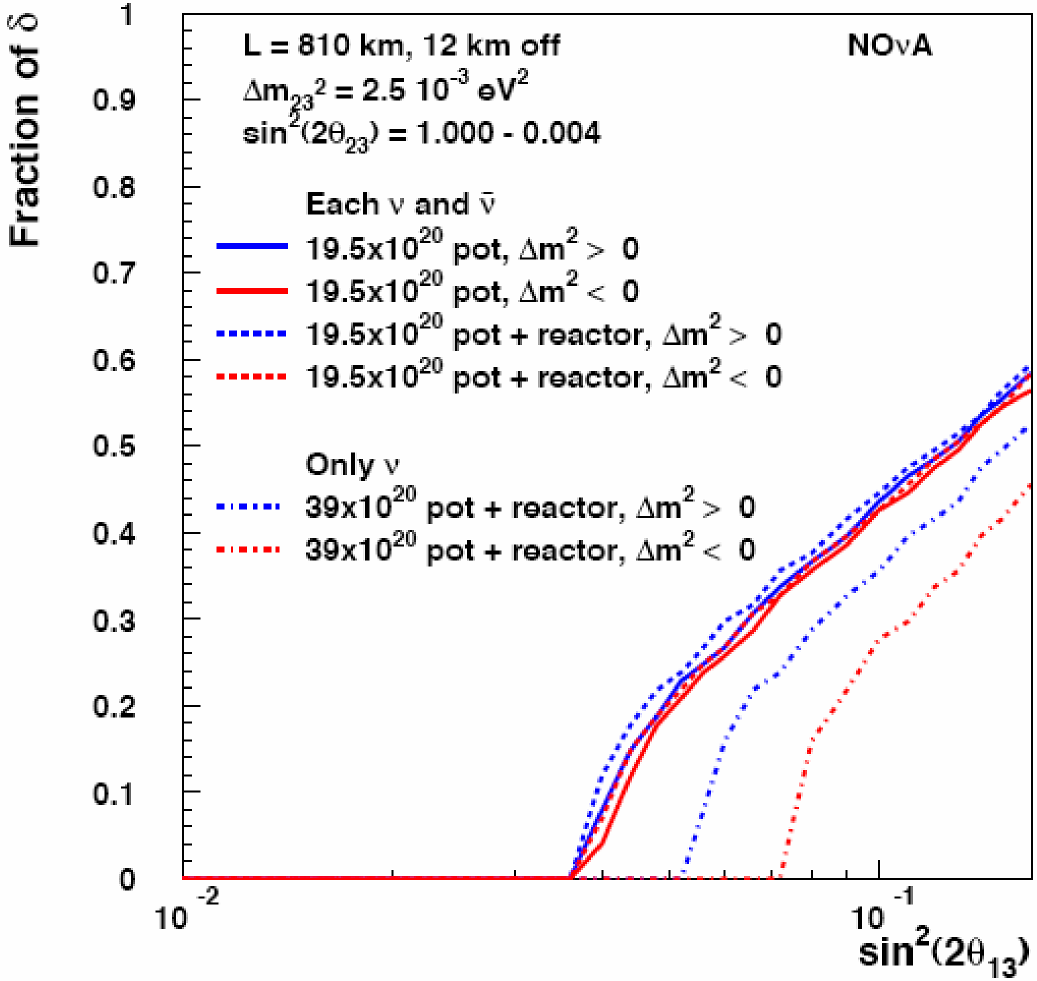
5 year ν only run

$3\ \sigma$ Sensitivity to $\theta_{13} \neq 0$
Comparison with a reactor experiment

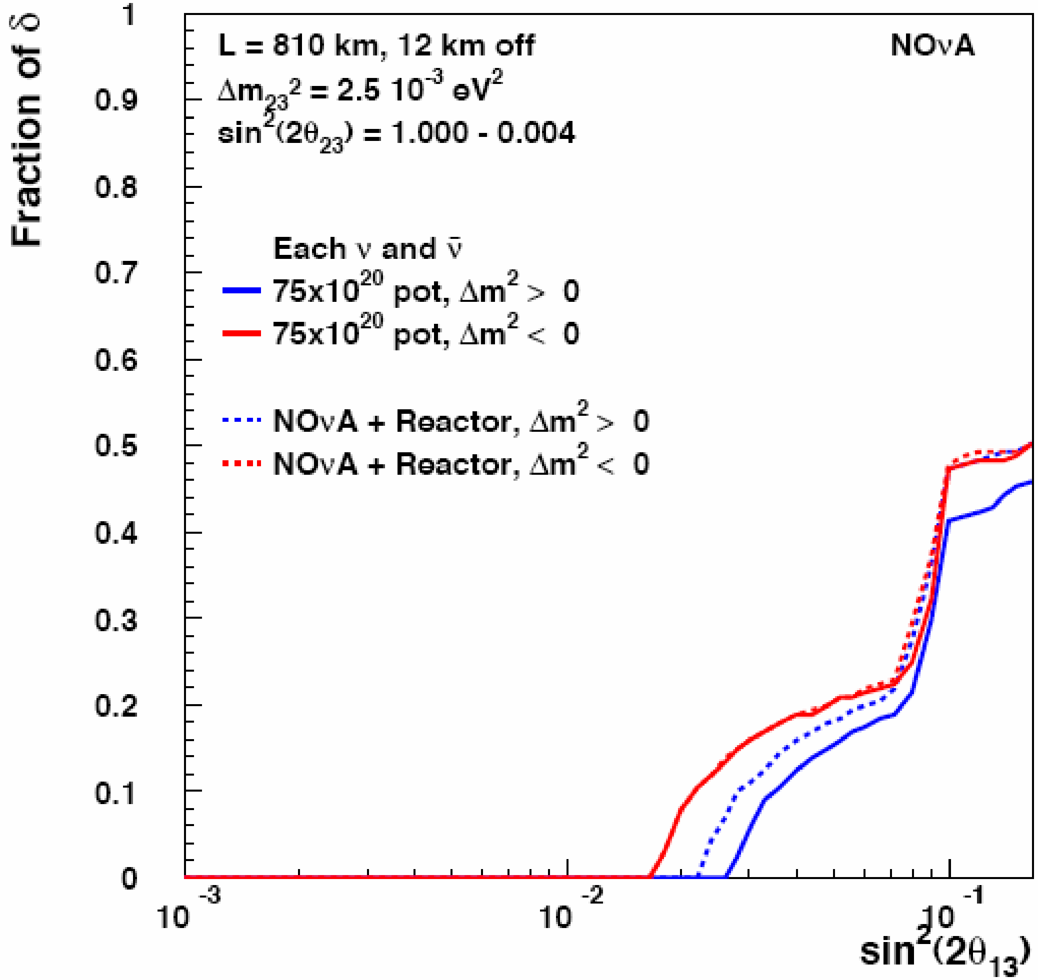


5 year
ν only
run

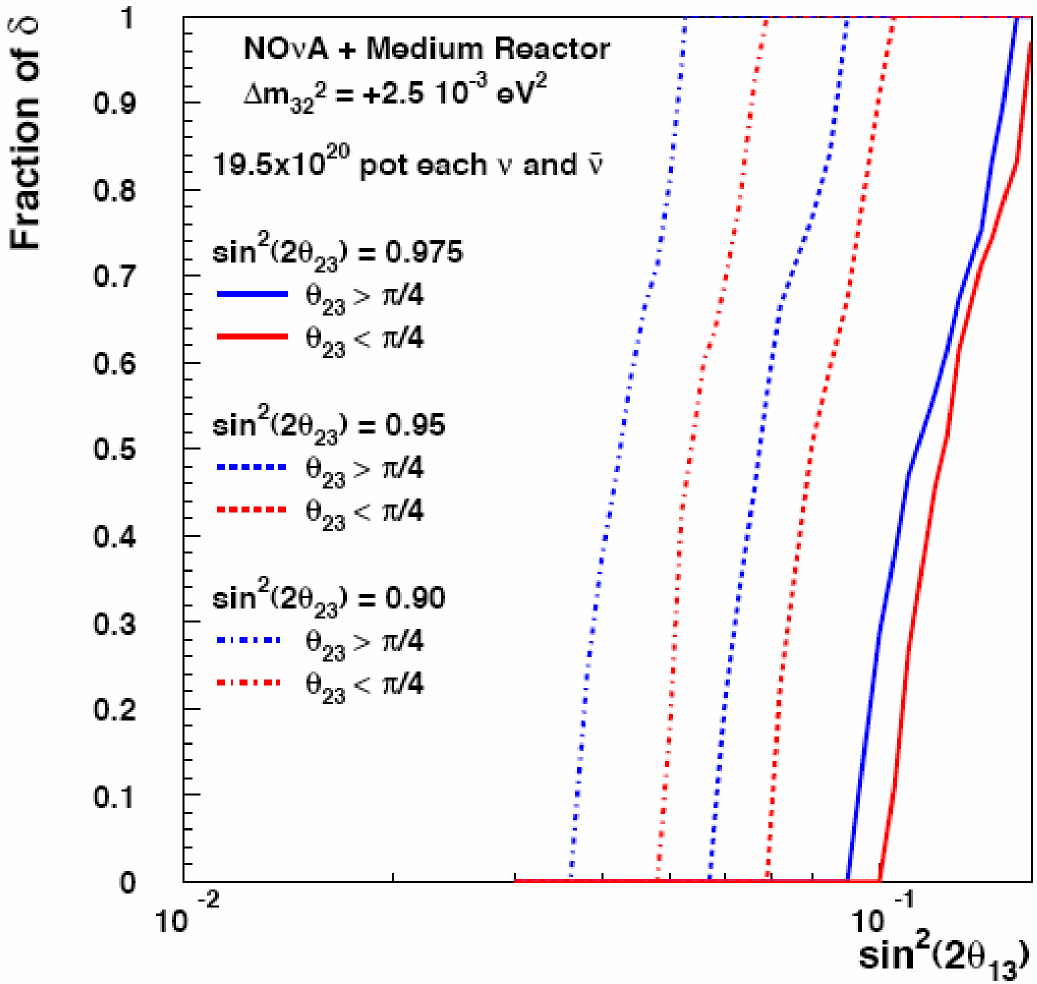
95% CL Resolution of the Mass Ordering: with a Reactor Expt.



3 σ Determination of CP Violation: with a Reactor Expt.



95% CL Resolution of the θ_{23} Ambiguity



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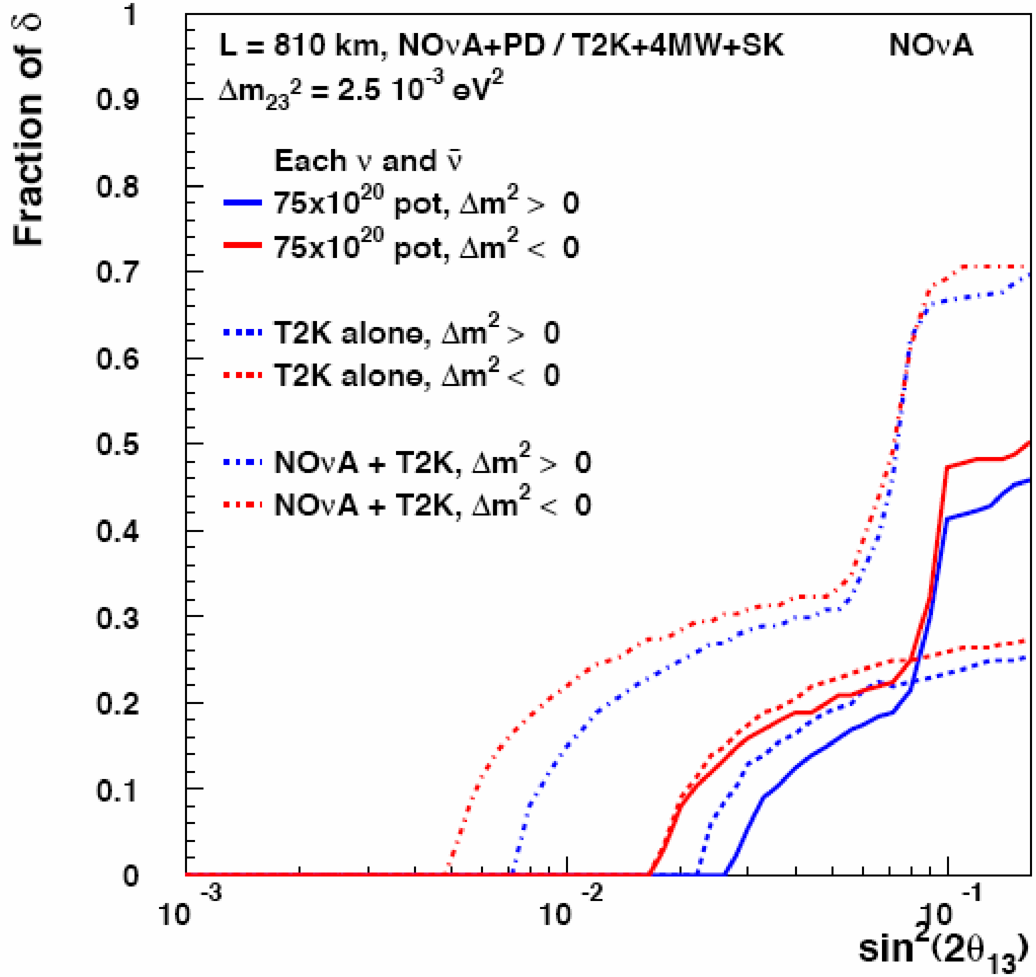

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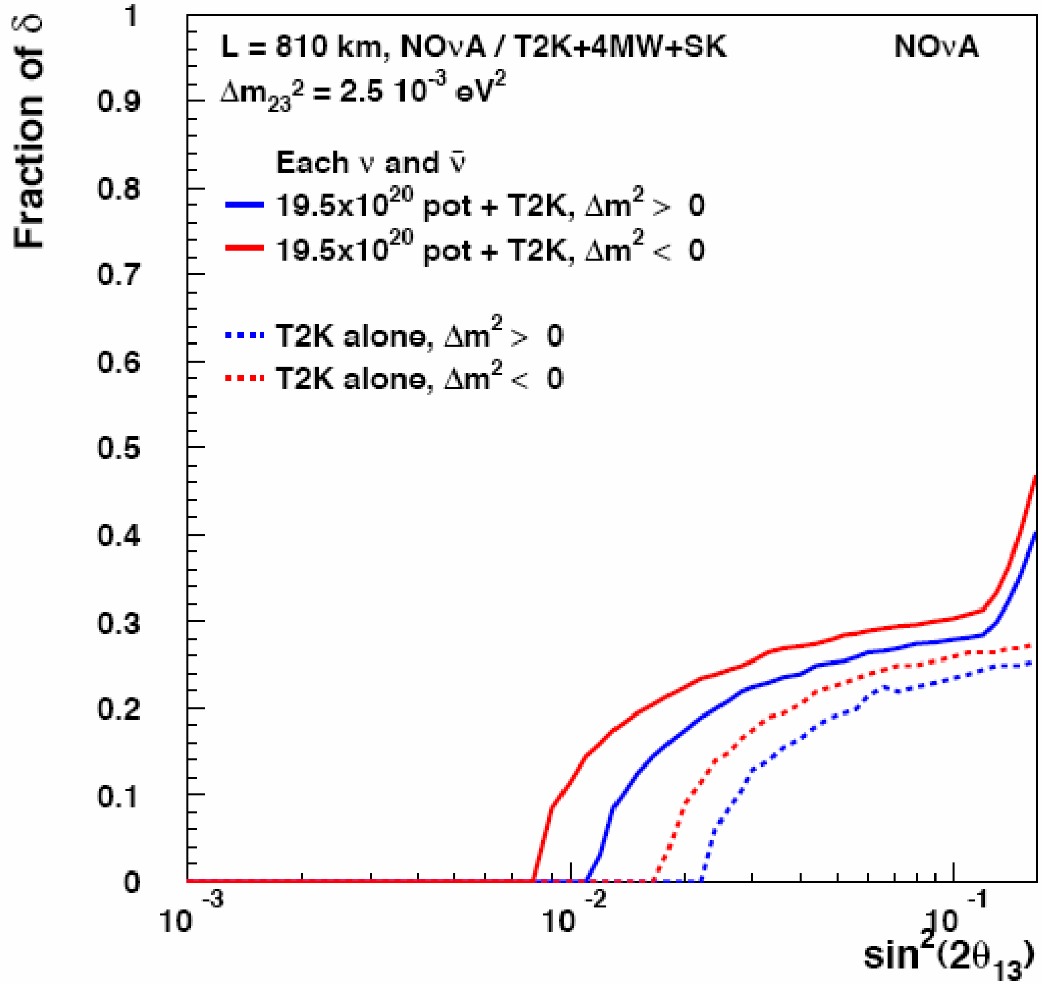

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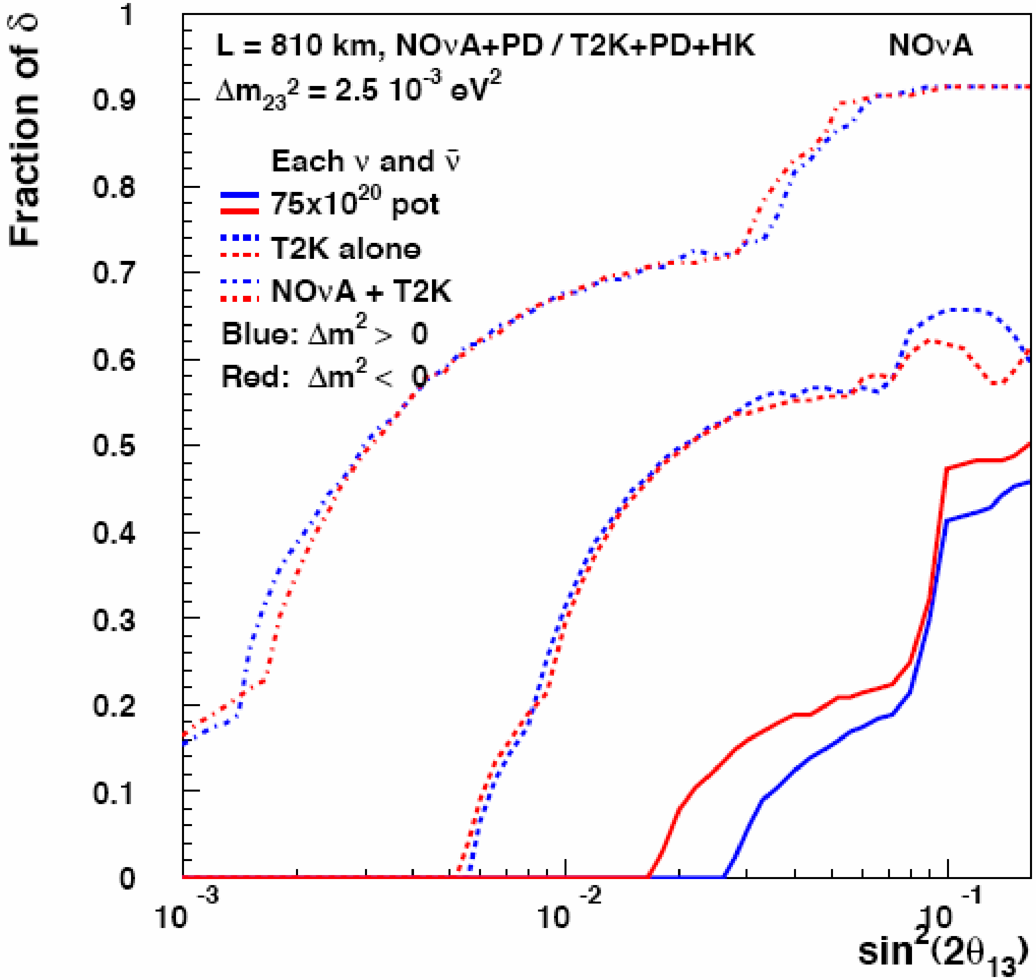
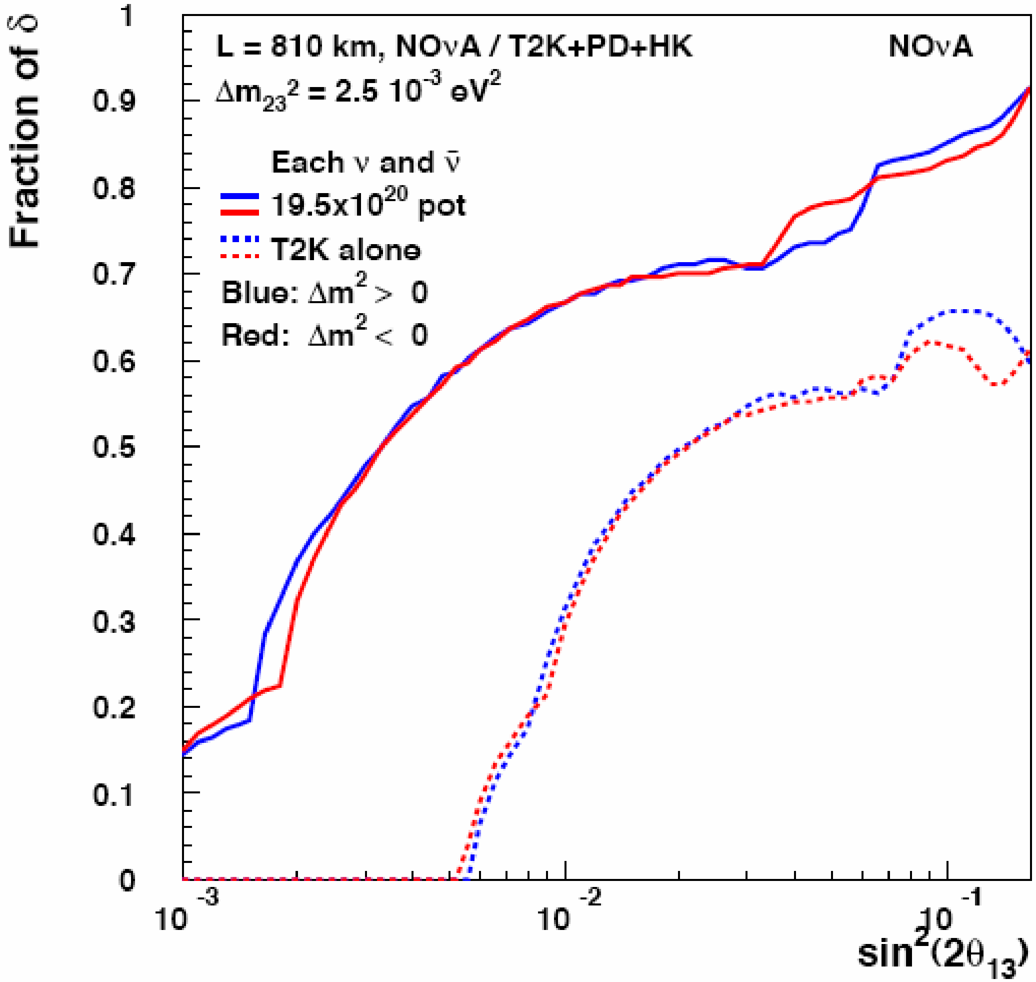
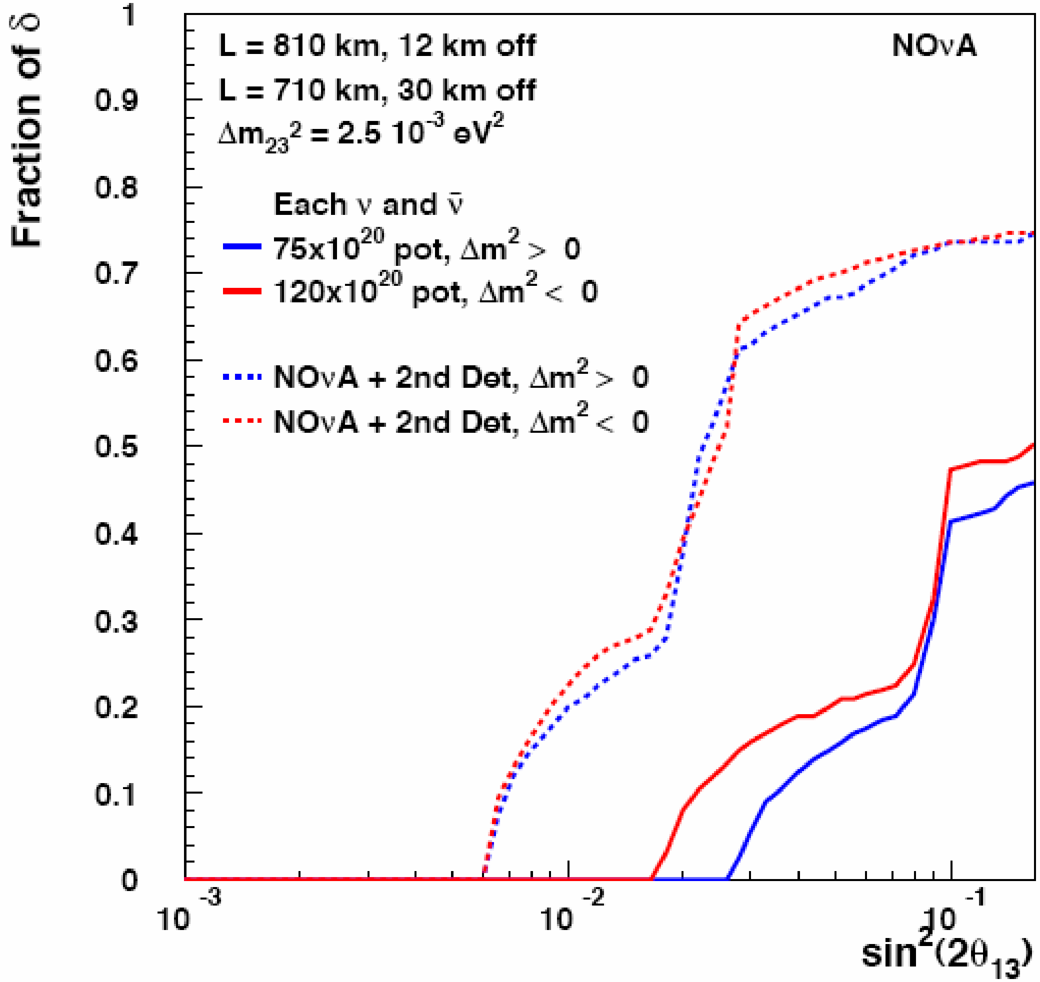


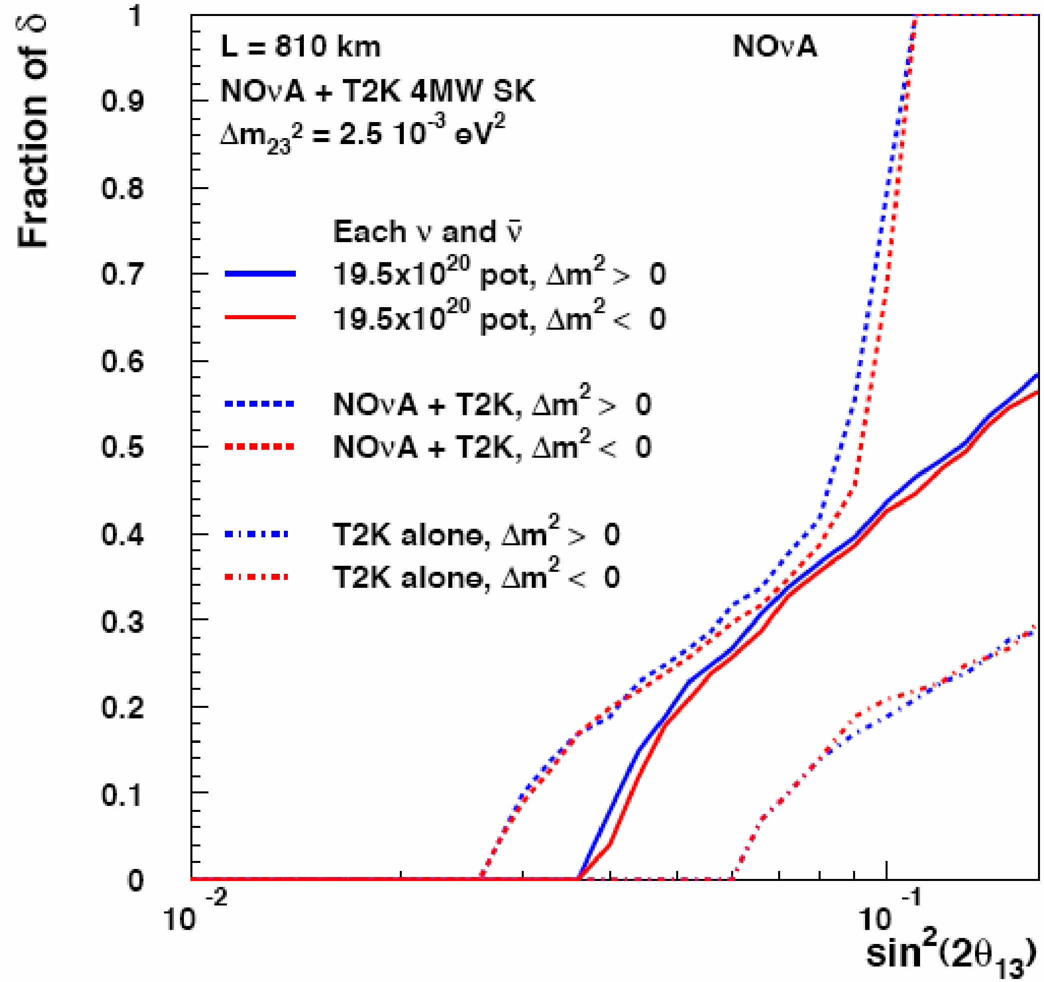
3 σ Determination of CP Violation



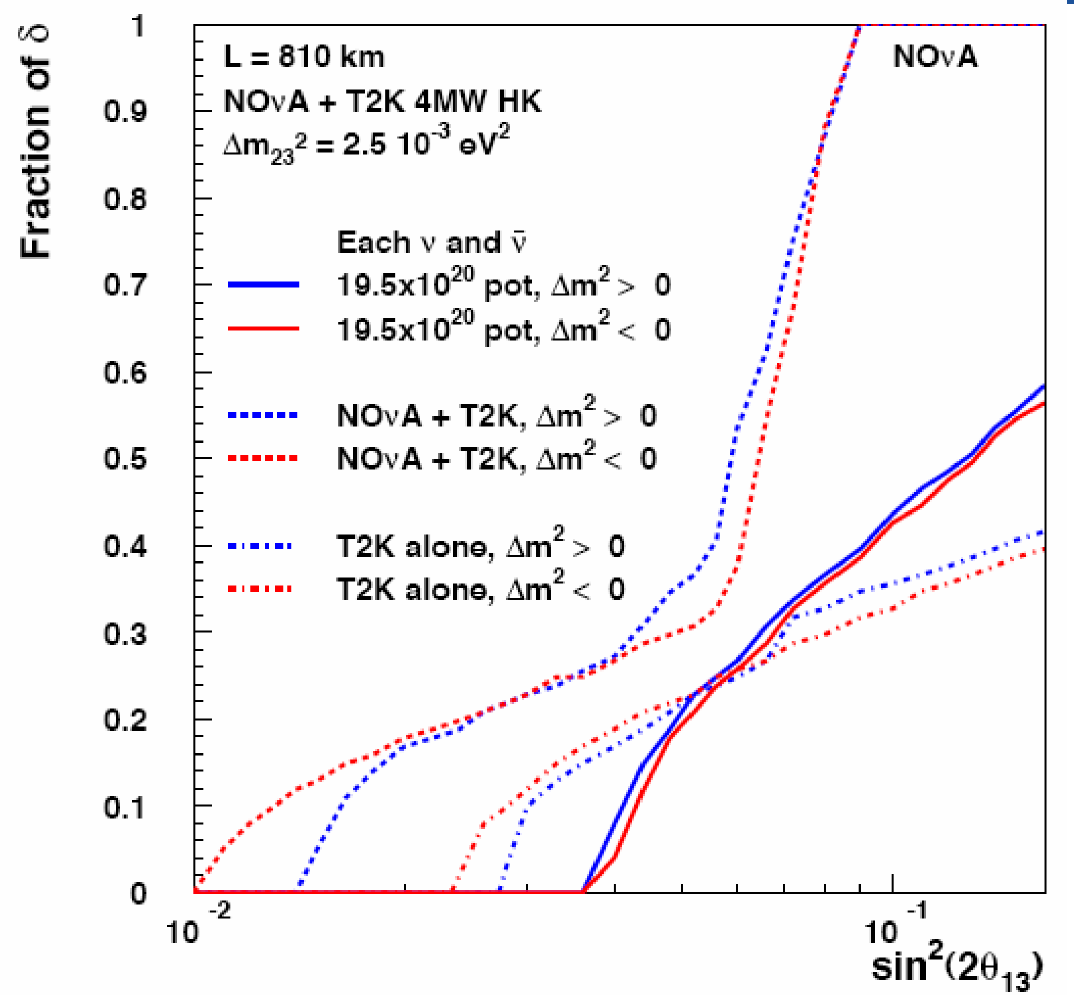
3 σ Determination of CP Violation



95% CL Resolution of the Mass Ordering



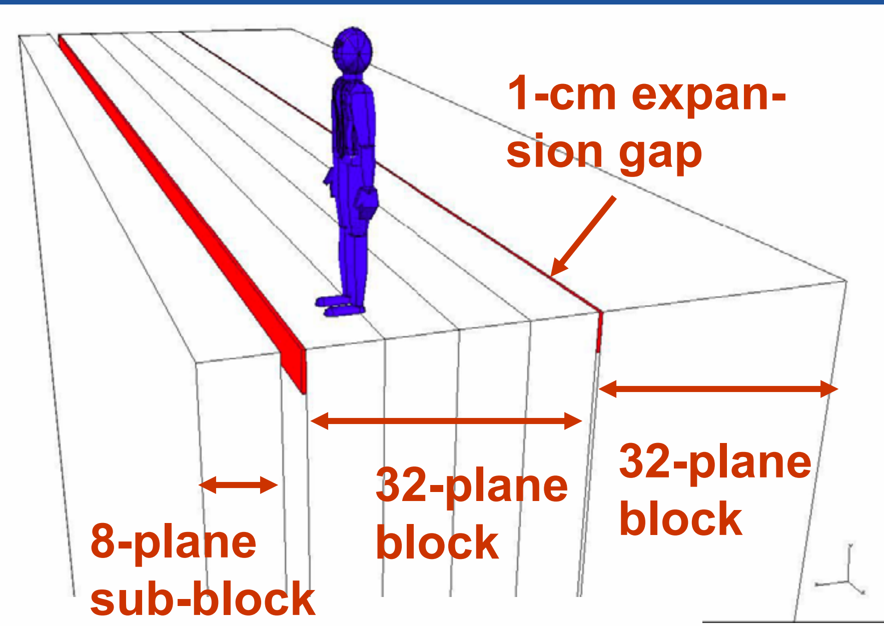
95% CL Resolution of the Mass Ordering

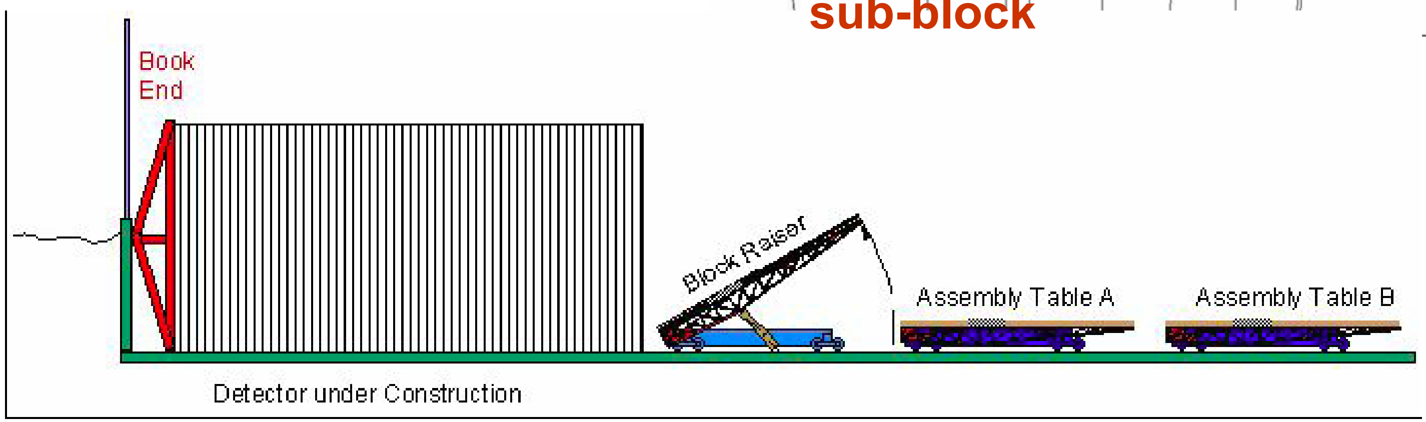


Far Detector Assembly

One 8-plane sub-block assembled per day

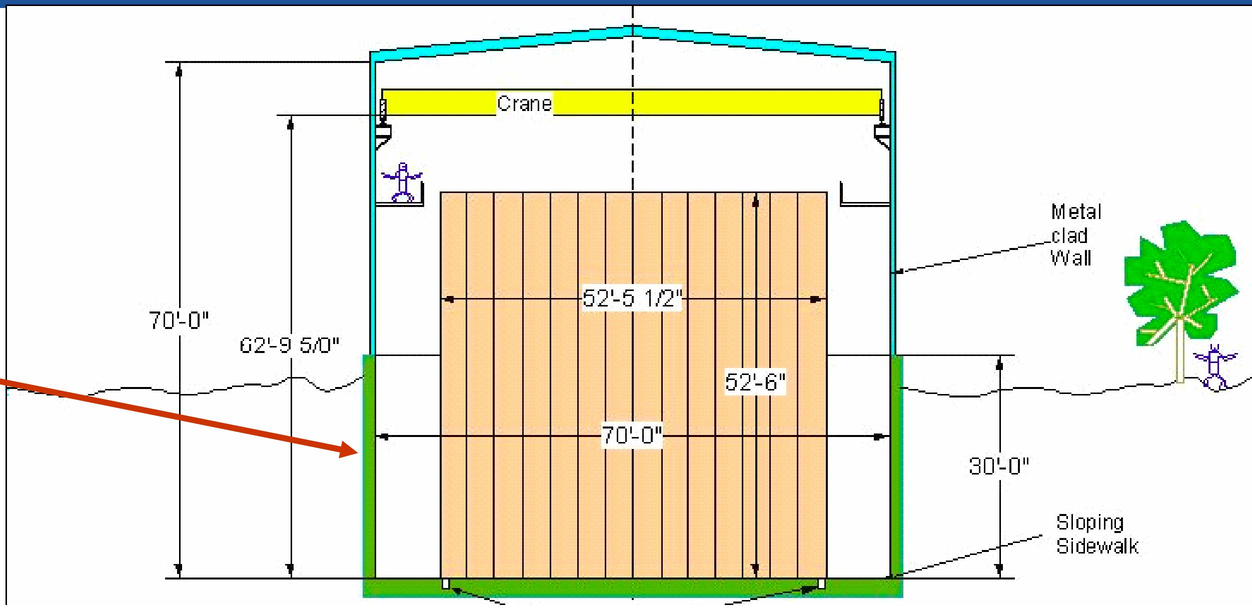
Detector has 248 sub-blocks

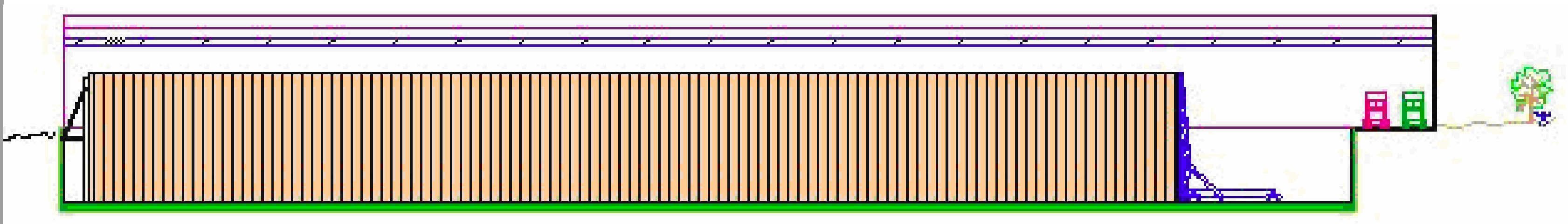




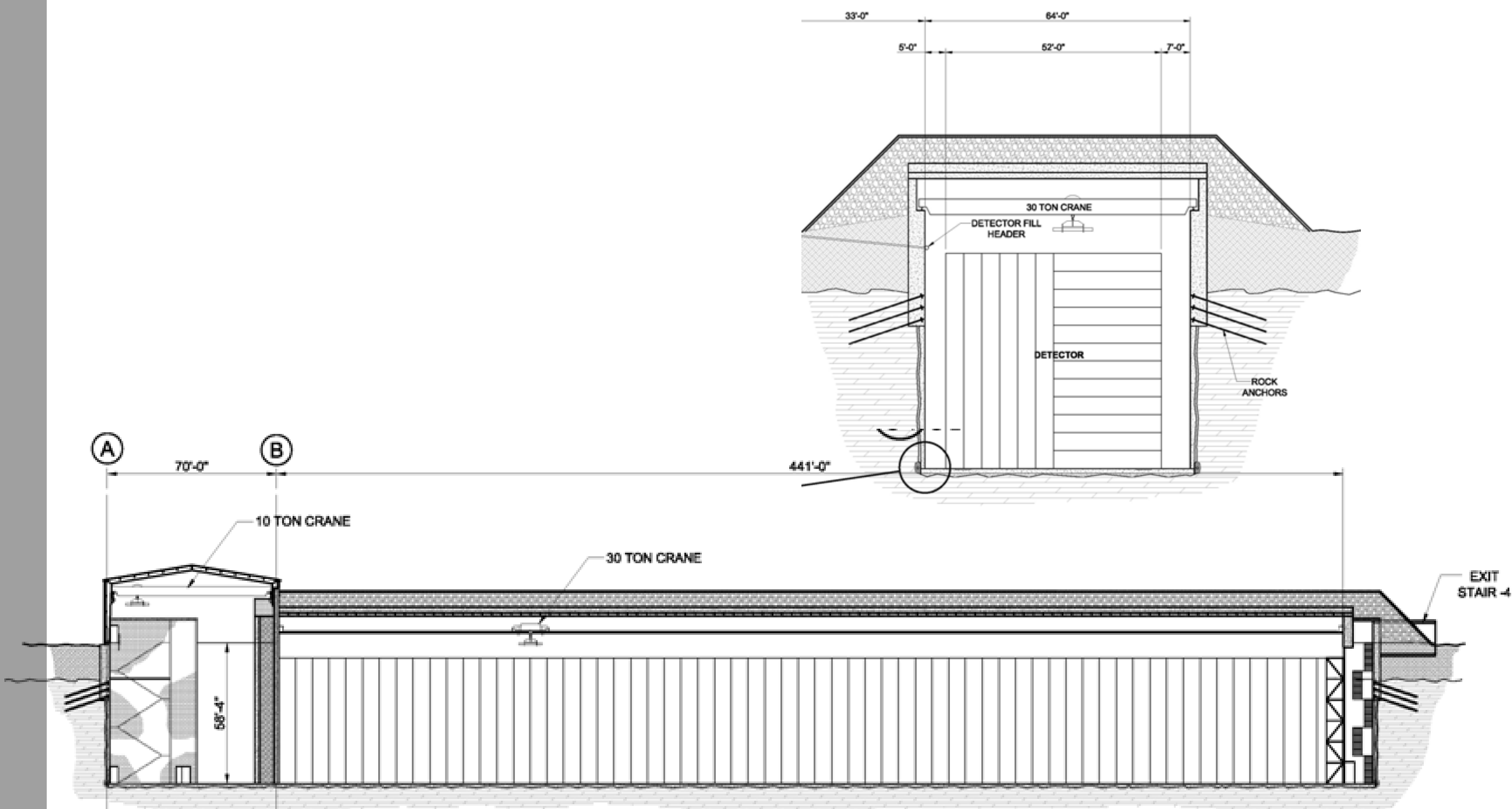
Far Detector Building
Proposal Design

Bathtub for full containment





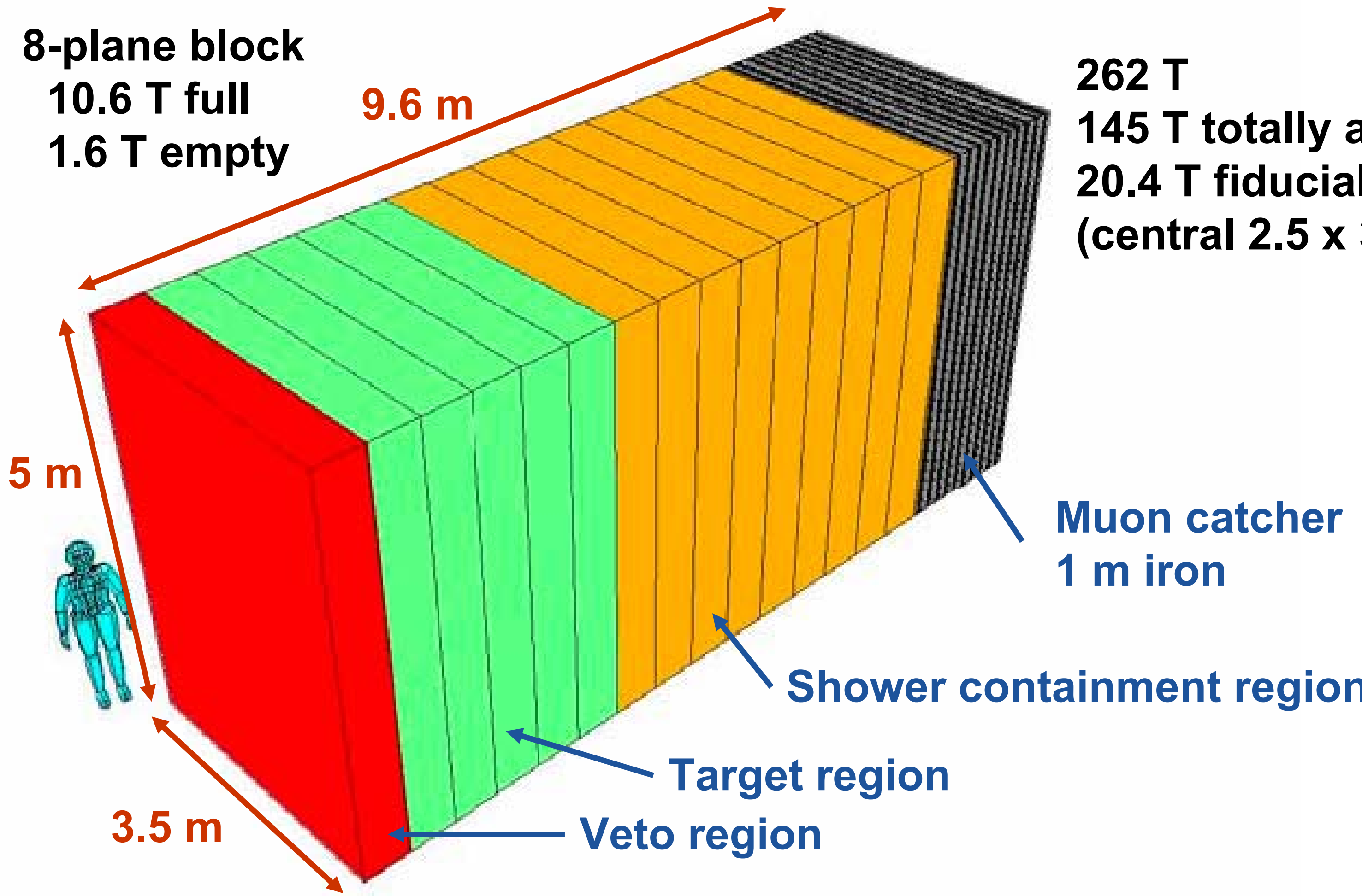
Far Detector Building
Design with Overburden



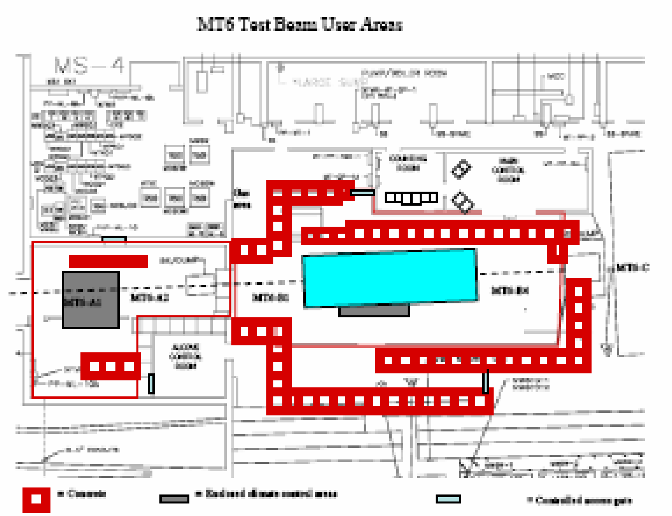
Near Detector

8-plane block
10.6 T full
1.6 T empty

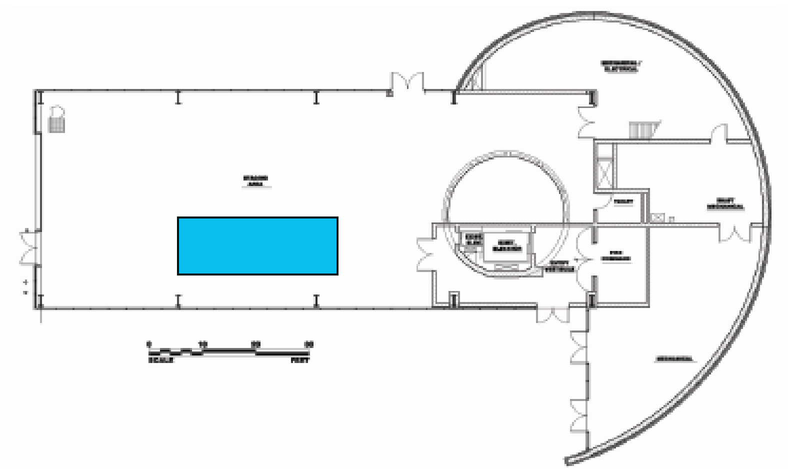
262 T
145 T totally active
20.4 T fiducial
(central 2.5 x 3.25 m)



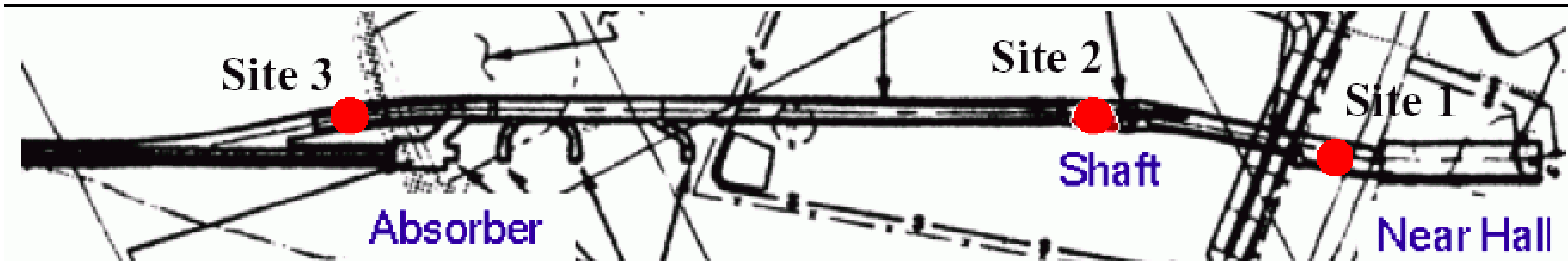
Near Detector: Modular and Mobile



M Test



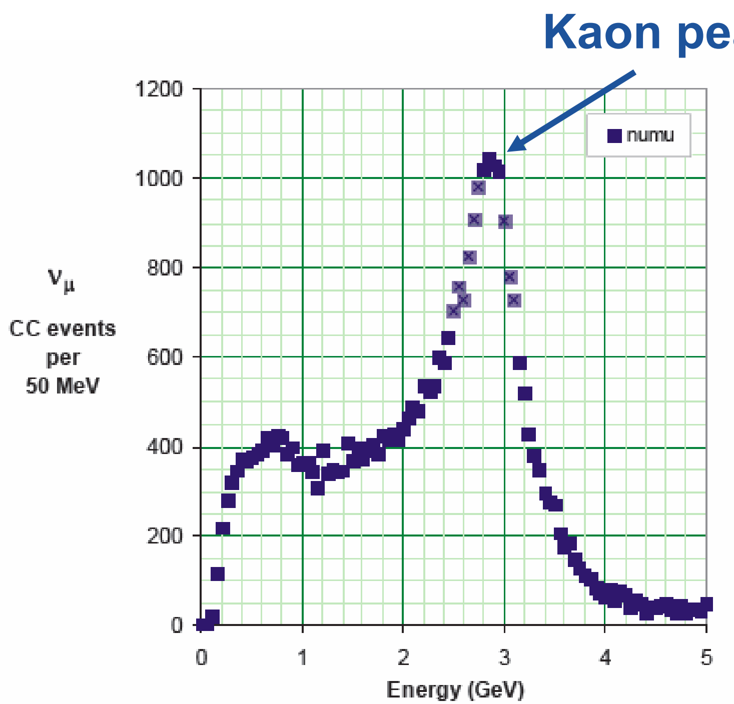
MINOS Surface Building



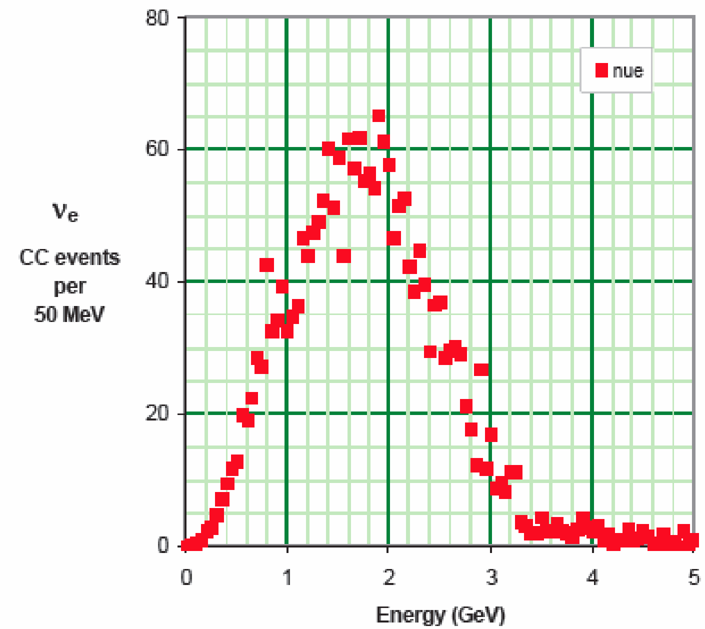
NuMI Access Tunnel

Near Detector in MINOS Surface Building

6.5 x 10^{20} pot in 75 mrad off-axis beam

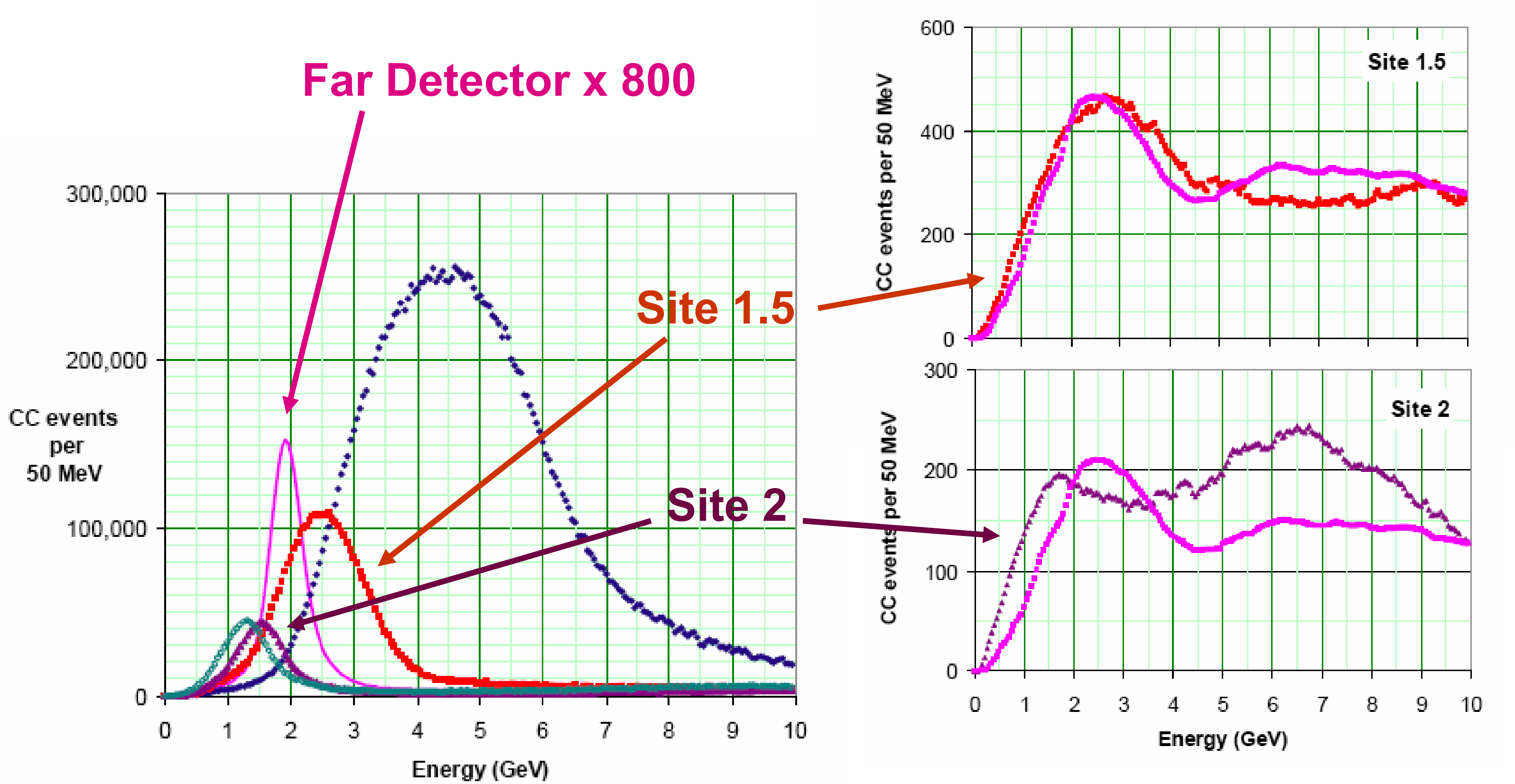


45,000 ν_μ CC events



2,200 ν_e CC events

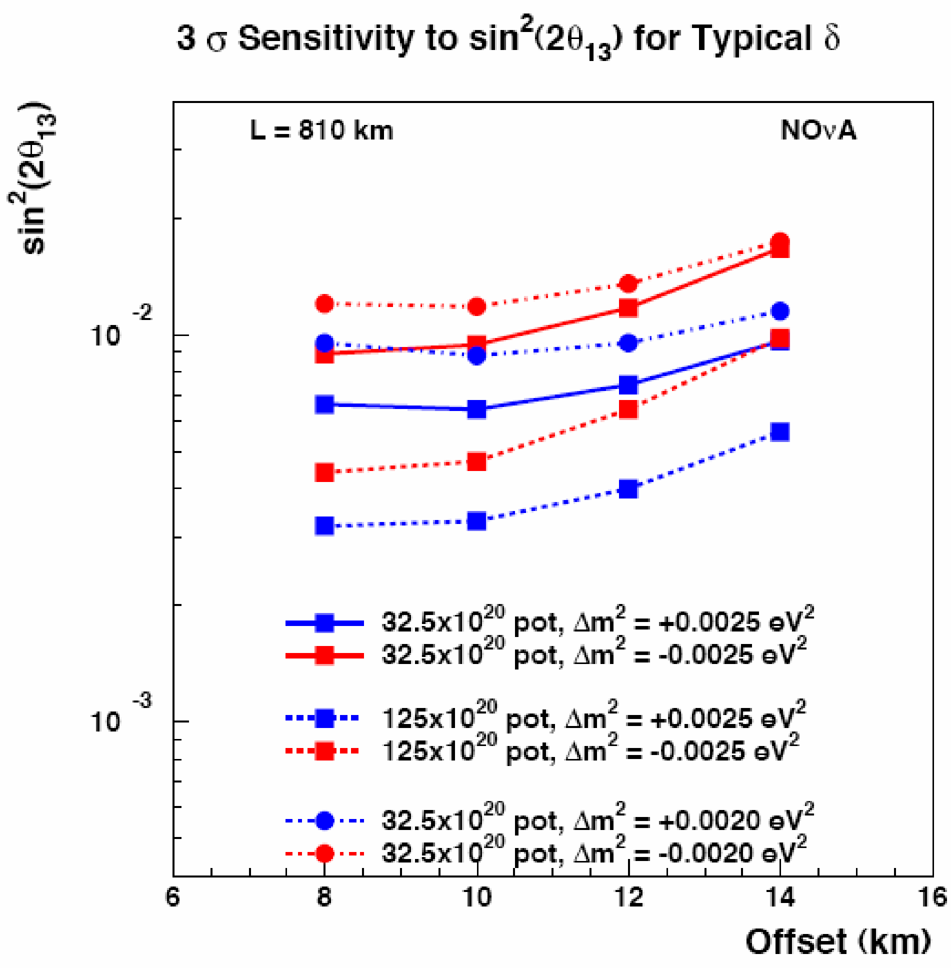
Near Detector in the Access Tunnel



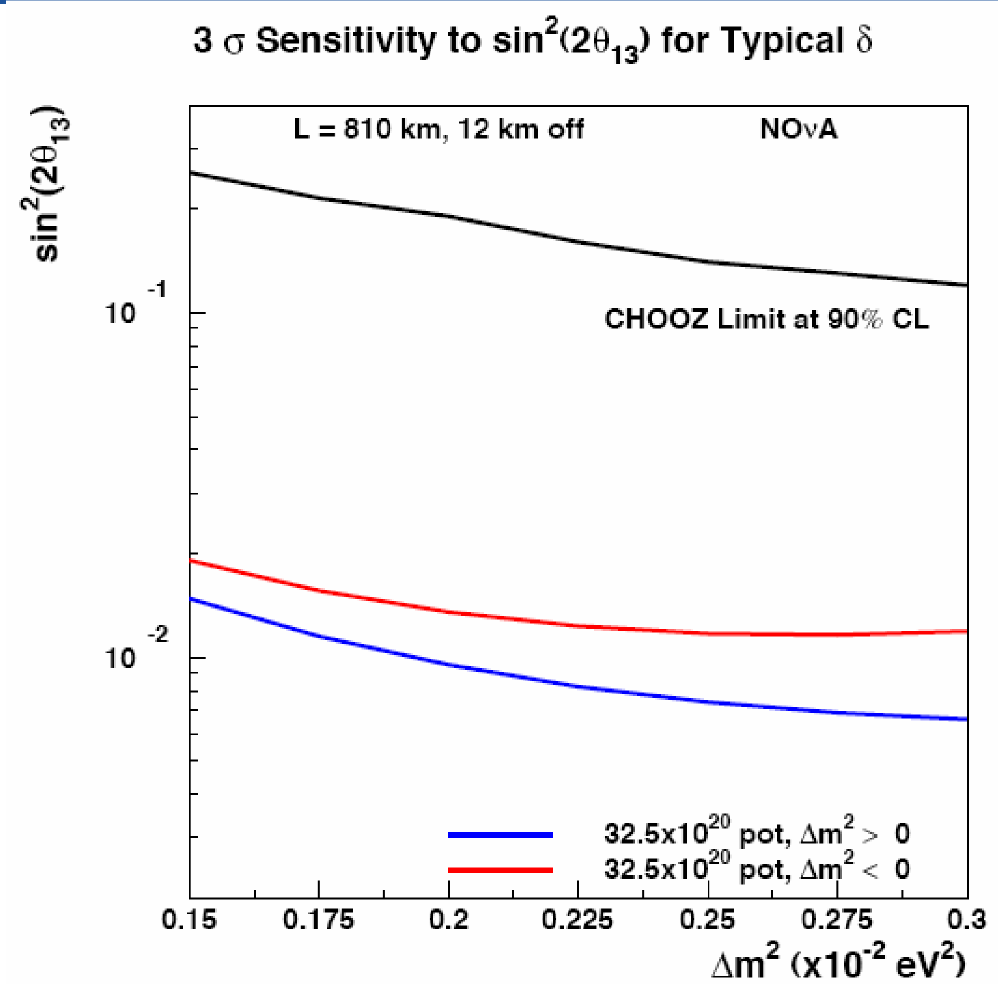
ν_μ CC events

ν_e CC events

Sensitivity to $\nu_\mu \rightarrow \nu_e$ Vs. Off-Axis Distance



Sensitivity to $\nu_\mu \rightarrow \nu_e$ Vs. Off-Axis Distance



Sensitivity to the Mass Ordering Vs. Off-Axis Distance